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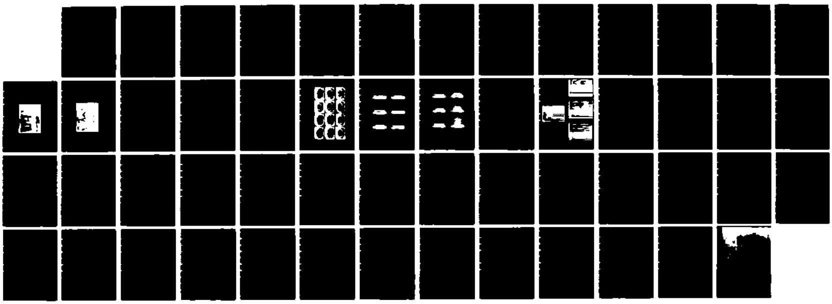

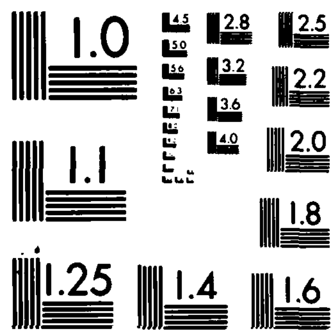

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Final Scientific Report

on the

THEORETICAL & EXPERIMENTAL INVESTIGATION OF COHERENT STRUCTURE IN THE TURBULENT BOUNDARY LAYER

AFOSR Contract No. F49620-78-C-0071

Reporting Period 1 May 1978 to 30 June 1983

by

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Results of a comprehensive analytical-experimental program examining the detail and implications of turbulent boundary layer flow structure are reported. The program combines both experimental flow visualization studies with analytical investigations of a series of phenomenological and theoretical models based upon three-dimensional, vortical flow structures developing and interacting in proximity to a solid surface. The experimental program has considered a range of sub-problems including the effect of surface modifications on low-speed streak formation and drag, and the effect of vortex loop inter-act

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with a solid boundary. To augment visual studies, a computerized interface with the video system has been developed which allows quantitative data to be obtained from flow visualization pictures. The specific thrust of the theoretical studies has been focussed on three reas: 1) how two and three-dimensional vortex structures interact with wall boundary layers; 2) the development of a new type of prediction method for two-dimensional turbulent boundary-layer flows; and 3) improvement in numerical techniques for solving parabolic, boundary-layer equations.

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I. Introduction

Over the past two decades, it has become increasingly evident that turbulence produced in boundary layers is a consequence of a complex series of organized events which generate and sustain a characteristic flow structure. It has also been shown in numerous studies that such flow structures can be repeatably detected and closely associated with the production of turbulence energy in boundary layers; thus, such structures are extremely important in both the dissipation of flow energy and increased fluid friction effects (i.e. drag). Basically, a turbulent flow structure is a flow pattern, normally associated with a concentration of fluid vorticity, which can be either observed or detected to occur in some quasi-repetitive fashion in time and space. Generally, a turbulent boundary layer appears to consist of a myriad of such flow structures, which occur over a range of scales; the type of flow structure which occurs depends on the location within the boundary layer, however, all of the flow structures are generated and interact in a terribly complex, but organized process. This process creates a physical situation wherein we have a complex mire of three-dimensional vortices moving in close proximity to solid surfaces.

The experimental and analytical difficulties created by the above flow behavior are numerous. To begin with, we have little understanding of the behavior of vortices and their subsequent effects in proximity to surfaces. Thus, it is unclear how to model the effects of these vortices such that their behavior can be implemented into improved turbulence models for a priori turbulence prediction methods. In addition, the present numerical prediction techniques are too limited to allow the proper implementation of such turbulence models.

To establish the types of flow structures present necessitates experimental techniques which can both detect and quantify the most typical flow structures present, particularly the three-dimensional behavior. Once typical turbulent flow structures have been hypothesized, analysis and experimental examination of these simplified flow structures can establish the key behavioral and interactive characteristics of these simpler structures. A detailed cross-comparison of the characteristics of these simplified structures can then be done to establish which flow structures best characterize fully turbulent behavior and how this information can best be implemented to 1) improve turbulence models and predictive schemes and 2) suggest methods for geometric or flow modifications which will reduce drag and flow separation effects.

The present report outlines the accomplishments of a combined analytical-experimental program which had the objective of examining the details of turbulent boundary layer structure by utilizing a procedure consistent with that outlined above. The broad objectives of the program has been to establish fundamental understanding of key vortical flow structures which appear to develop in proximity to a surface during turbulence production, and to develop techniques to:

1) Simulate and predict the two and three-dimensional characteristics of these vortical flow structures, particularly adjacent to solid boundaries;
2) Develop both improved turbulence prediction models based on the identified behavior of the vortical structures and the requisite numerical procedures to facilitate the implementation of these models;

3) Establish the effects of geometric modifications which augment or negate the vortical structure effects and examine the subsequent effects on surface drag.
4) Develop improved techniques for the experimental detection, analysis, and presentation of three-dimensional, turbulent-type flow behavior.

II. EXPERIMENTAL PROGRAM

A. Overview

Over the five year contract period, a comprehensive facility for turbulence and three-dimensional flow structure studies has been developed and employed for a cohesive series of investigations examining the structure of turbulent boundary layers. The basic approach of the experimental program has been to examine the flow behavior in turbulent boundary layers, attempting to establish the degree of coherent motion which may be present and suggesting characteristic flow "structures" which are responsible for the observed motions/behavior. The observations and models suggested by these general studies then provide the input for both the companion analytical studies and for experimental simulation studies, as well as guiding further, more detailed studies of both 1) the basic flow structure and 2) methods for modification of the structure to achieve reduction/amplification of surface transport phenomena (i.e. skin friction, heat transfer, mass transfer). Due to the complex, three-dimensional nature of turbulence, the major experimental technique employed has been flow visualization, augmented by selected probe studies. Particular effort has been made to fully develop the flow visualization techniques employed, using the most modern recording/analysis methods available in order to develop the capacity for simultaneous multi-view studies as well as to move toward automated quantitative evaluation of flow fields using visual data.

To appropriately discuss both the facilities developed and the results of the various experimental investigations, the following research discussion is subdivided into five complementary areas: 1) Facilities development, 2) Identification and quantification of turbulence structure characteristics, 3) Control of turbulence structure, 4) Simulation of hypothesized turbulence flow structures, and 5) Recreation of 3-D motion in a turbulent boundary layer using computer augmented display of video information.

B. General Experimental Facilities

During the period of the contract, a general experimental facility was developed to support the various turbulent boundary layer structure experiments. The following section gives a brief description of the characteristics of this facility; a more detailed description of the facility is given in Smith and Metzler (1983) or Smith and Schwartz (1983). In addition, specific systems or test sections employed for particular studies will be described in conjunction with those studies.

All the studies described in this report were performed in a free-surface water channel facility with a 6m working section, 0.9m wide by 0.3m deep. A general schematic of the cross-section of the working section with associated equipment is shown in Figure 1.

Visualization of the flow structure and behavior was done using a variety of specially designed hydrogen bubble-wire probes which allow a 25mm dia. platinum wire to be oriented either transverse or normal to the flow direction. The hydrogen bubble-lines are generated using a specially designed generator unit, built in our laboratory. Using the probes and generator, lines and sheets of hydrogen bubbles can be introduced either parallel or normal to a test surface at any desired height and frequency.

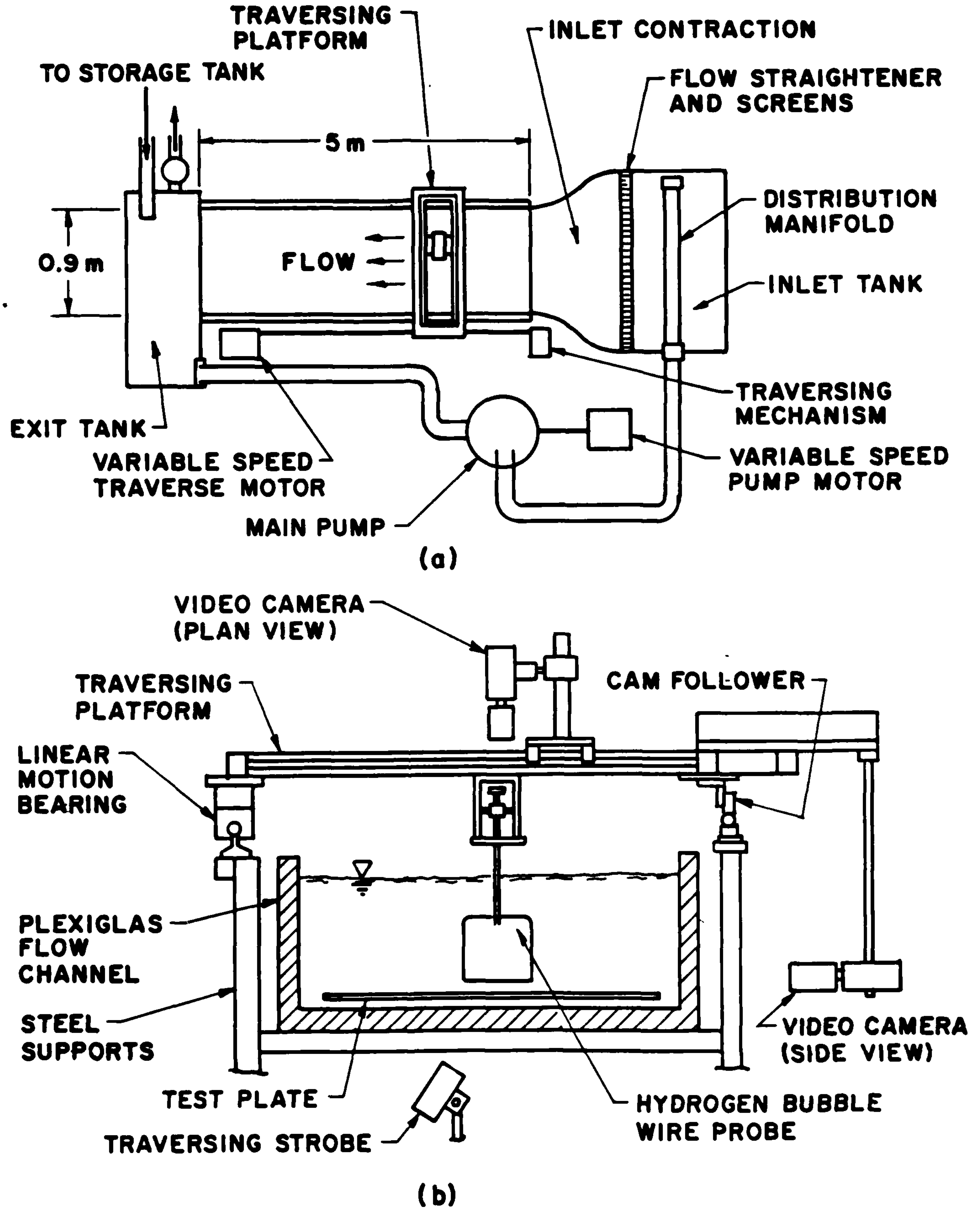


Figure 1. Free-Surface Water Channel: (a) schematic of flow facility; (b) end-on view of test section (looking downstream)

The viewing and recording system employed in the studies is a two-camera, high-speed video system (manufactured by the Video Logic Co.) which incorporates synchronized strobe lights to provide 120 frame/s with effective frame exposure times of 10^{-4}s. A split-screen capability allows two different fields of view to be simultaneously displayed and recorded. All recorded data can be played in flicker-free slow motion (both forward and reverse), as well as single-framed for detailed data analysis and hard copy output. For some studies, a specially designed fiber optic lens, 1 cm in diameter and 1 m long, was incorporated with one of the video cameras to yield end-on views of the hydrogen bubble-wire [see Smith & Schwartz, 1983; also Schwartz, 1982].

Once a video sequence is recorded, conventional still photographs of individual stop-action frames can be taken directly from the video screen. Detailed descriptions of the visualization system are presented further in Smith (1981) and Smith (1983a).

C. Turbulent Structure Characteristics

To provide a focus to our investigations of turbulent boundary layer structure it was decided to direct our primary attention to the structure in the wall and near-wall regions of the boundary layer. The rationale for this was that the most coherent structure (low-speed streaks) and the most energetic turbulence producing event (the "bursting" behavior) occur in these regions, and it stands to reason that these events must play a very prominent, if not the dominant role in controlling the integrated effects of turbulence, such as surface drag. These studies both 1) extended our understanding of the quantitative characteristics of near-wall turbulent structure and 2) explored the causative mechanisms of the structure, developing improved understanding and interpretations of the turbulence production cycle.

Using a bubble-wire oriented transverse to the flow direction (figure 1), top-view sequences of the flow behavior in the region $1<y^+<40$ were obtained and the detailed characteristics of the low-speed streak structures which dominate the very near-wall region of turbulent boundary layers were examined for a Reynolds number range of $740 \leq Re_\theta \leq 5830$ [Smith & Metzler, 1983]. The low-speed streak pattern was found to be essentially identical in appearance and character for all Reynolds numbers examined. Using visual counting techniques for extended video sequences, the statistics of non-dimensional spanwise spacing of the low-speed streaks were determined and shown to be essentially invarient with Reynolds number, exhibiting consistent values of mean non-dimensional spanwise spacing ($\bar{\lambda}^+ = \lambda u_\tau/\nu \cong 100$) and remarkably similar probability distributions conforming to lognormal behavior. Further studies showed that streak spacing increases with distance from the wall due to a merging and intermittency process whcih occurs for $y^+ \gtrsim 5$. An additional observation was that although low-speed streaks are not fixed in time and space, they demonstrate a tremendous persistence, often maintaining their integrity and reinforcing themselves for time periods up to an order of magnitude longer than the observed bursting times associated with wall region turbulence production. This persistence behavior is illustrated quite clearly by Figure 2 [from Smith and Metzler, 1983] which indicates the temporal persistence of streaks as identified using a systematic visual counting technique.

A further investigation of streak persistence and longevity was carried out through an experiment which capitalized upon the observation that stray particulate matter on the channel bottom appeared to resolve itself into

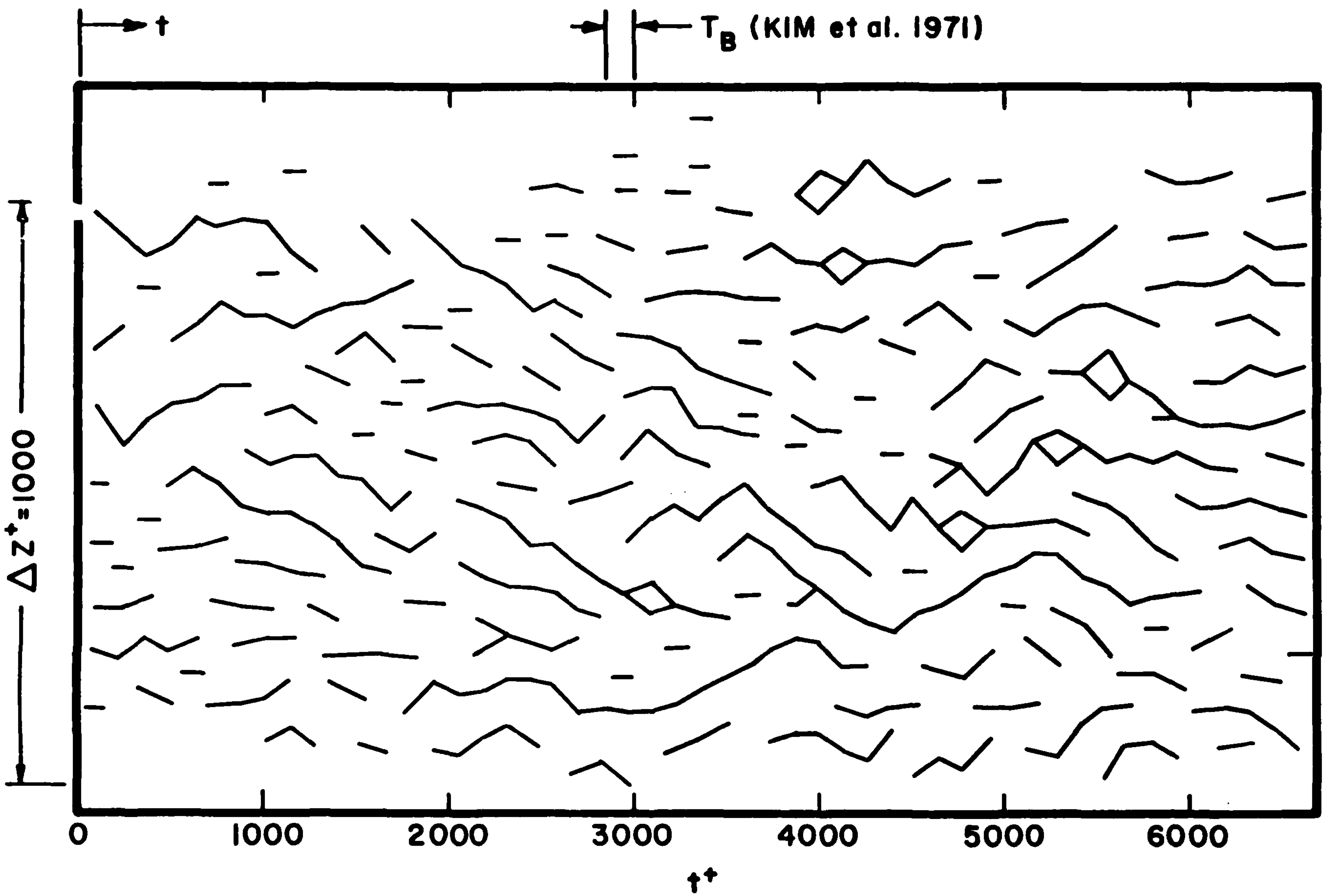


Figure 2. Streak persistence graph indicating continuous behavior of identified streaks

long streamwise aggregations. This study [Metzler, 1981] involved the injection of a thin slurry of 100 μm glass beads (s.g. $\cong$ 2 and $d^+ = 1$) along the surface beneath a fully turbulent boundary layer. Within a few seconds after injection the beads collected into streamwise concentrations of width $\Delta z^+ \cong 35$ which extended essentially uninterrupted the length of the channel with a nearly uniform spanwise spacing of $\Delta z^+ \cong 80$. This pattern appeared stable and quasi-stationary, with the only movement being a quasi-periodic buffeting and a gradual downstream migration of the beads, apparently in response to localized velocity fluctuations. Further investigation with a horizontal hydrogen bubble-wire disclosed that the bead concentrations essentially coincided with the low-speed streaks.

The bead concentration studies suggested that some streamwise mechanism which occurs in a repetitive fashion must be responsible both for the extreme streamwise length of the bead concentrations and for the formation of low-speed streaks. In an attempt to reveal both the presence and the characteristics of the streamwise behavior, a dual-view study [Smith and Schwartz, 1983; Schwartz, 1981; Smith et. al., 1981] was conducted using a fiber-optic lens to obtain simultaneous top-end views of the near-wall region within which low-speed streaks are observed. A schematic of the physical configuration is illustrated in Figure 3.

Figure 4 shows an example of a dual-view bubble-line pattern obtained using the above visualization system. The top-view of the series of periodically generated bubble-lines reveals the wall-region streak pattern (i.e. the alternating regions of fast and slow-speed flow near the surface). However, since all the bubble-lines are moving toward the end-view lens, the motion of individual bubble-lines cannot be discriminated, only the collective behavior. This integrated view of the bubble-lines severely limits the determination of the three-dimensional behavior.

To facilitate the determination of local motion, single-realization bubble-lines were used. This entails the generation of only single bubble-lines, the motion and deformation of which can be followed over the entire extent of the viewing field. Figure 5 is an example of a single bubble-line observed in dual-view. Obviously, the same alternating fast and slow-speed regions can be observed in top-view, but the relative vertical motion can be more clearly detected in the end-view.

Detailed observation of these single bubble-line pictures indicated not only discretely spaced spanwise upwellings of low-speed fluid, but frequent deformation of these upwellings into "mushroom" and counter-rotating double-loop patterns. Repeated observation of these mushroom and double-loop patterns revealed quite clearly that they are the resultant patterns created by a pair of counter-rotating streamwise vortical structures in proximity to the wall.

Detailed examination of a series of dual-view sequences over a wide range of Reynolds numbers and y^+ values has shown the low-speed streaks to always be regions of vertical motion, with the bubble-line patterns frequently revealing associated streamwise rotation (40% of observations) or counter-rotating vortex pairs (15-20% of observations). Evaluation of the characteristics of the vortical motions indicate that they are fairly substantial in extent and strength, with streamwise vortices observed to occur over a range in dimensionless diameters of $10<Du_\tau/\nu<40$ and mean vorticities from $0.05<\omega_x\nu/u^2_\tau<0.6$ in the near-wall region. Generally, the characteristics of observed counter-rotating vortices varied with wire location from the

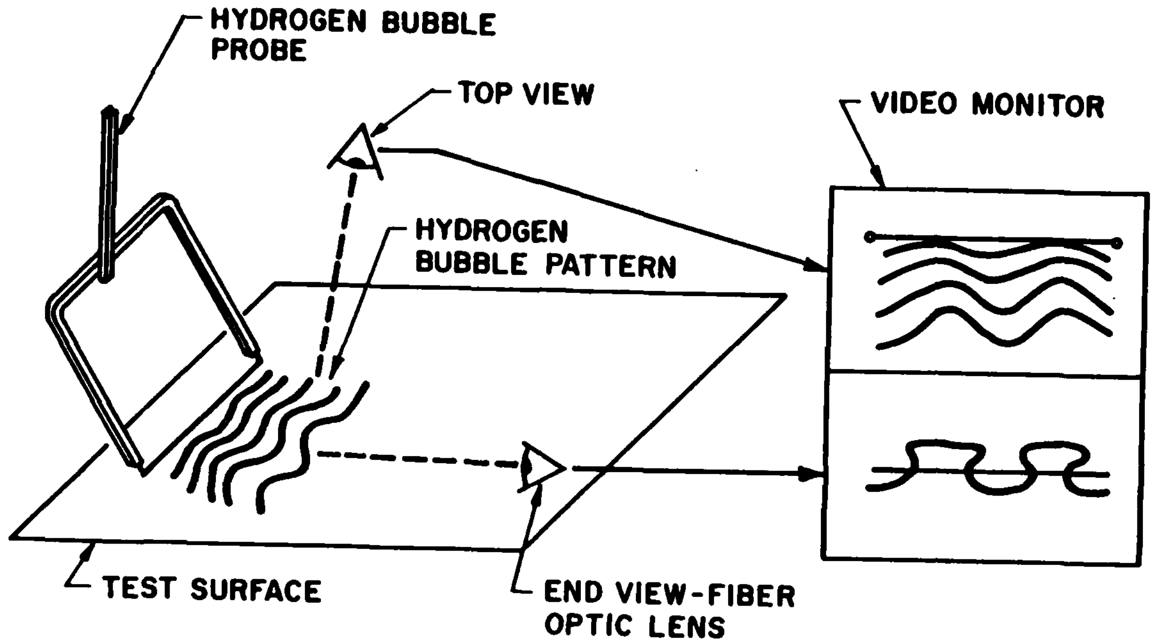


Figure 3. Technique for split-screen viewing and display of near-wall turbulent behavior

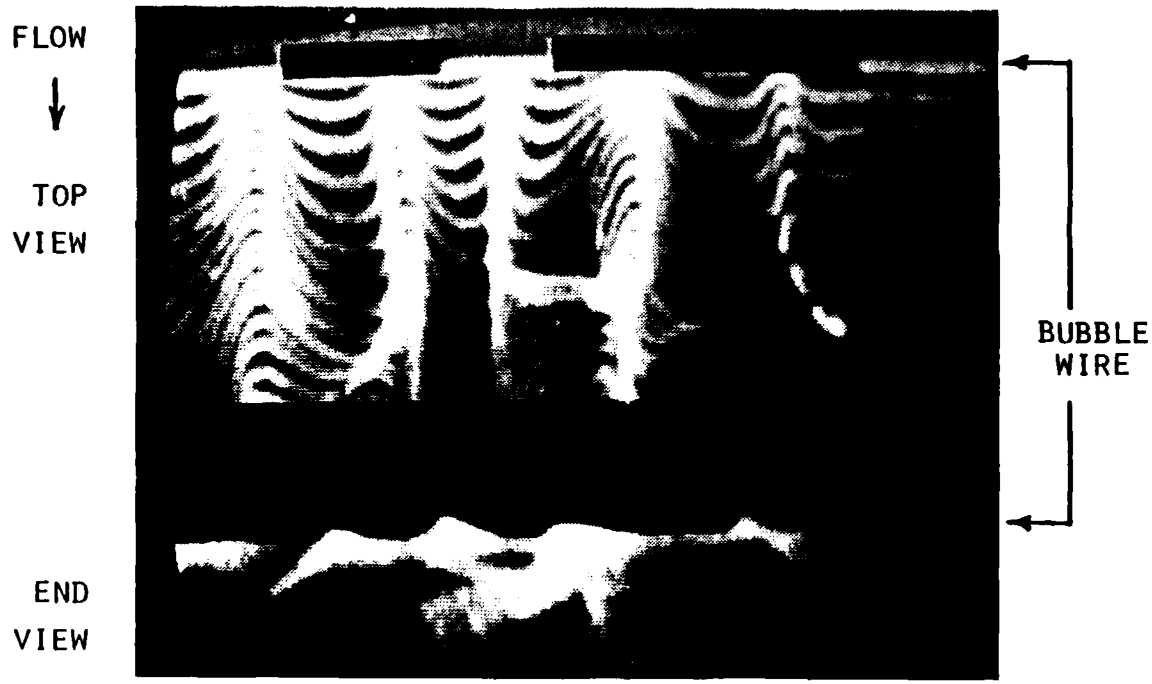


Figure 4. *Dual-View, multiple bubble-line pattern of near-wall turbulent boundary layer behavior.* $Re_\theta = 1700$, $y^+_{wire} = 0$.

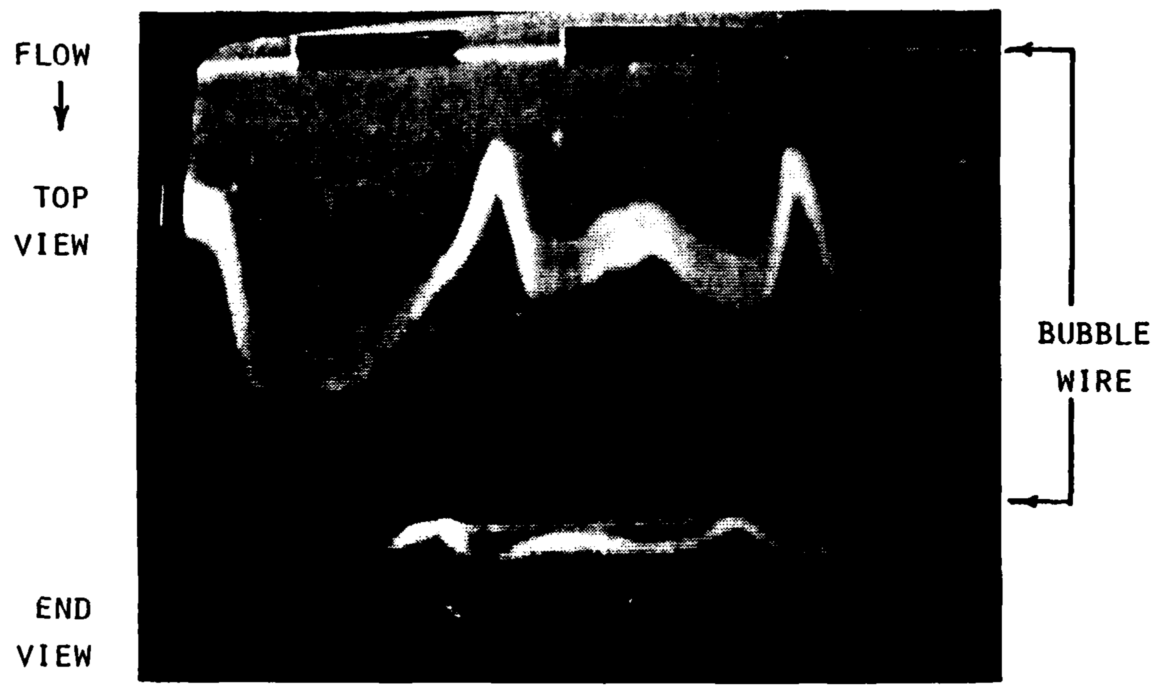


Figure 5. Dual-view, single bubble-line pattern for same conditions as Figure 4

wall [Schwartz, 1981], with $y^+ \simeq 25$ indicated as the most probable location for detecting a vortex center. In addition, the apparent diameter and strength of the observed streamwise vortices were generally larger the farther from the wall the vortices were detected.

Probably the most important observation from this dual-view study was that whenever counter-rotating vortices were detected in end-view, they were <u>always</u> observed in the corresponding top-view to evolve either from or in conjunction with a pattern indicating a low-speed streak. Thus, it was apparent that the presence of counter-rotating, streamwise vortices is either necessary for or the result of low-speed streak formation.

D. Turbulence Control

The observation of low-speed streak "persistence" and the apparent stabilization of the lateral location of low-speed streaks by the agglomerations of glass beads suggested that spanwise surface perturbations elongated in the streamwise direction could potentially function as "formation sites" for development of the low-speed streaks. To carefully examine this suggestion a study was done employing a combination of hydrogen bubble-wire flow visualization and hot-film anemometry measurements to examine the effects of sublayer scale streamwise surface modifications on near-wall flow structure [Johansen and Smith, 1983].

Using monofilament fishline of an approximate nondimensional height of $h^+ = 4$, the effects of nondimensional spanwise line spacings for $60<S^+<160$ were examined. The results indicate that the lines appear to act as nucleation sites for low-speed streaks, as illustrated by the comparative streak spacing histograms in Figure 6. Statistical evaluation of streak stabilization effects indicated that the presence of the lines had the greatest effect for $S^+<100$, but that for $y^+>10$ the stabilizing effect of the lines on streak behavior diminished for all line spacings examined, with the near-wall behavior relaxing back toward that characteristic of an unmodified surface. The confinement of the effect of the lines to the very near-wall region was borne out by measured mean velocity and turbulence intensity profiles, which indicated discernable variations from unmodified flat plate behavior only for $y^+<30$. In essence, the sublayer surface modifications examined appear to influence turbulent structure behavior only in the very near-wall region, indicating that despite the forced organization of the low-speed streak regions adjacent to the wall, this organized effect is lost quite rapidly a short distance above the wall.

By integration of the velocity profiles using momentum integral techniques, it was determined that surface drag is increased slightly by the presence of the surface modifications. This is felt to be due to an increased effectiveness in momentum transport created by increased spanwise organization of the streaks, which in effect makes the surface a more efficient momentum transport surface (and thus higher drag).

In a follow-on study of surface modification effects on turbulence, two riblet-type surfaces as developed by NASA Langley have been and are still under study. Initial results indicate that the effects of the riblets are confined to regions quite near the surface ($y^+ \lesssim 6$ to 10). Within this very thin layer, low-speed regions of extent commensurate with the riblet spacing seem to be present, but merge quickly into what appear to be

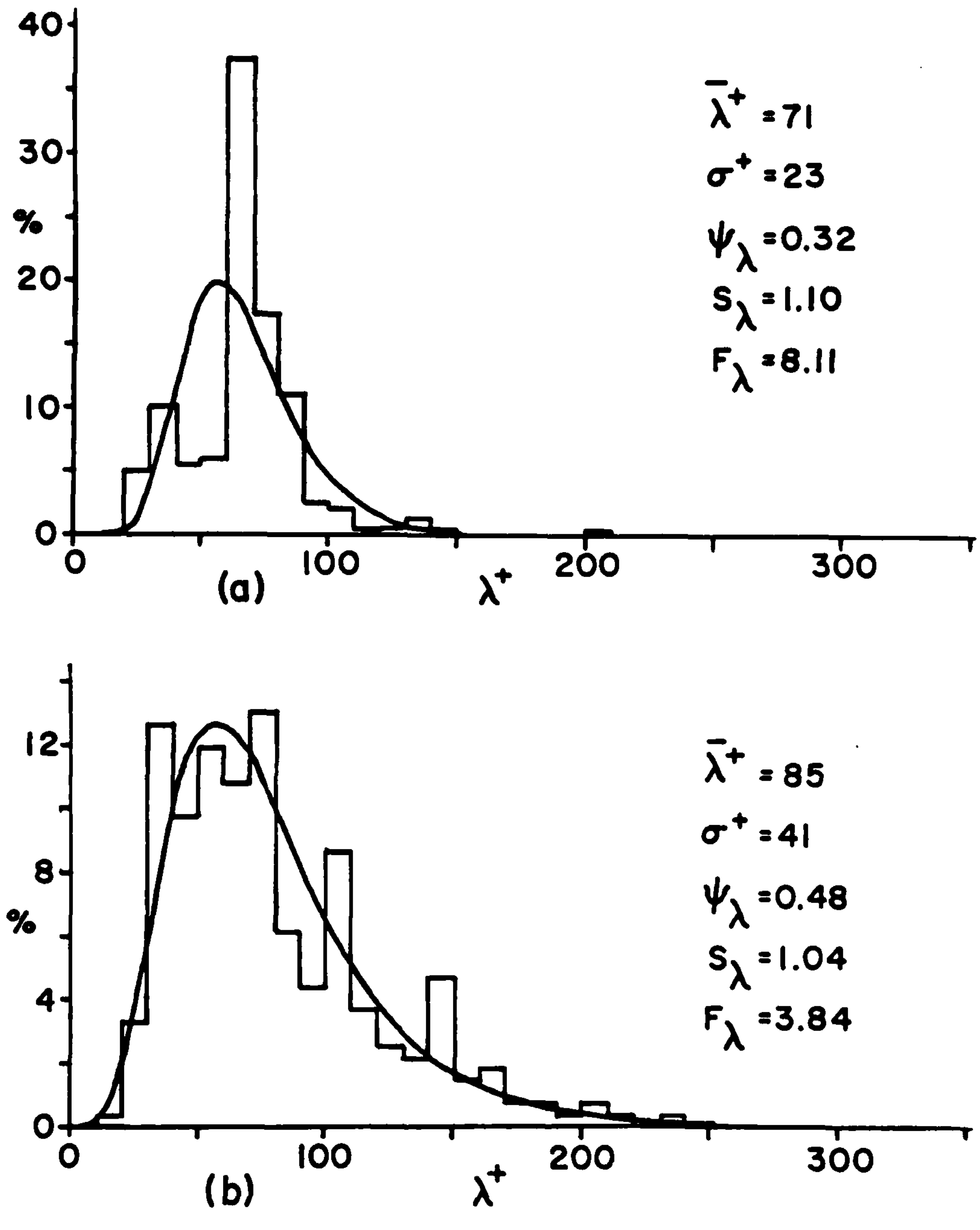


Figure 6. Comparative low-speed streak probability distributions, Re_θ = 2500 and y^+_{wire} = 5, for (a) unmodified flat plate, and (b) streamwise, cylindrical surface modifications, h^+ = 4.

conventionally spaced low-speed streaks for $y^+ \gtrsim 8$ to 10. However, the overall activity level seems to be reduced (i.e. bursting). It appears that the riblets create a thicker, more stable sublayer due to the increased cross-stream surface resistence caused by the riblets. Thus, the riblets apparently constrain the very near-wall fluid such that it resists the lateral influences which form the streaks, creating streaks which are probably more stable, break down less frequently, and are less efficient at momentum transfer. Reduction of momentum transfer results in reduced surface friction effects, which has been illustrated by NASA to be the case for the surfaces examined.

Detailed visualization and probe studies of the riblet surfaces are continuing to examine the validity of the above lateral transport theory. If it is shown to be valid, this would suggest that turbulence inhibitors (and thus drag reducing surfaces) must be configured to restrain lateral, spanwise transport in turbulent boundary layers.

E. Turbulence Simulation

The premise upon which the Lehigh turbulence program and a number of other programs across the country are based is that complex turbulent flows are "built" of different "flow structures." However, determining the basic flow structures and extracting their role from the complex entanglement of fluid motion which is turbulence is an extremely difficult task, complicated by the fact that we do not understand the behavior of some of the simpler flow structures which have been speculated to be the constituents of turbulence. Therefore, during the contract period, we have conducted detailed investigations of the behavior of two simple flow structures which appear to have the potential for modeling some of the key characteristics of turbulent boundary layers.

The simplest of the flow structures is the interaction of a vortex ring as it impacts a solid surface. During this impact process, a complex inviscid-viscous interaction takes place which generates (as predicted by the parallel analytical results) secondary and tertiary vortices. The resulting group of vortices then interact in a very three-dimensional, but symmetric fashion to rapidly disperse the vorticity of the initial vortex. Over the past several years of the contract period, a very extensive study has been done (Cerra and Smith, 1983) of over 90 different combinations of vortex parameters for a range of laminar vortices with $200 < Re_0 < 3500$. It has been determined that the behavior during and following vortex impact is very repeatable for a fixed set of conditions, but the characteristics of the interaction vary significantly with initial Reynolds number.

The basic process during the interaction is the formation of discrete vortices of opposited rotation to the original vortex, which either 1) coalesce with the original vortex, causing a rapid spreading the total system vorticity or 2) actually eject from proximity of the original vortex, sending a discrete vortex ring back along the impingement path of the original vortex ring. Figure 7, which illustrates case 1 above, shows a top view of a vortex impact with a surface covered with dye demonstrating the extreme three dimensionality of the interaction process. Figure 8 illustrates the second case above, i.e. that an impacting vortex can create a secondary vortex ring which "rebounds" back in opposition to the direction of travel of the original vortex ring. It is felt that this latter effect may have implications, although indirectly, to the bursting and ejection behavior observed in a turbulent boundary layer.

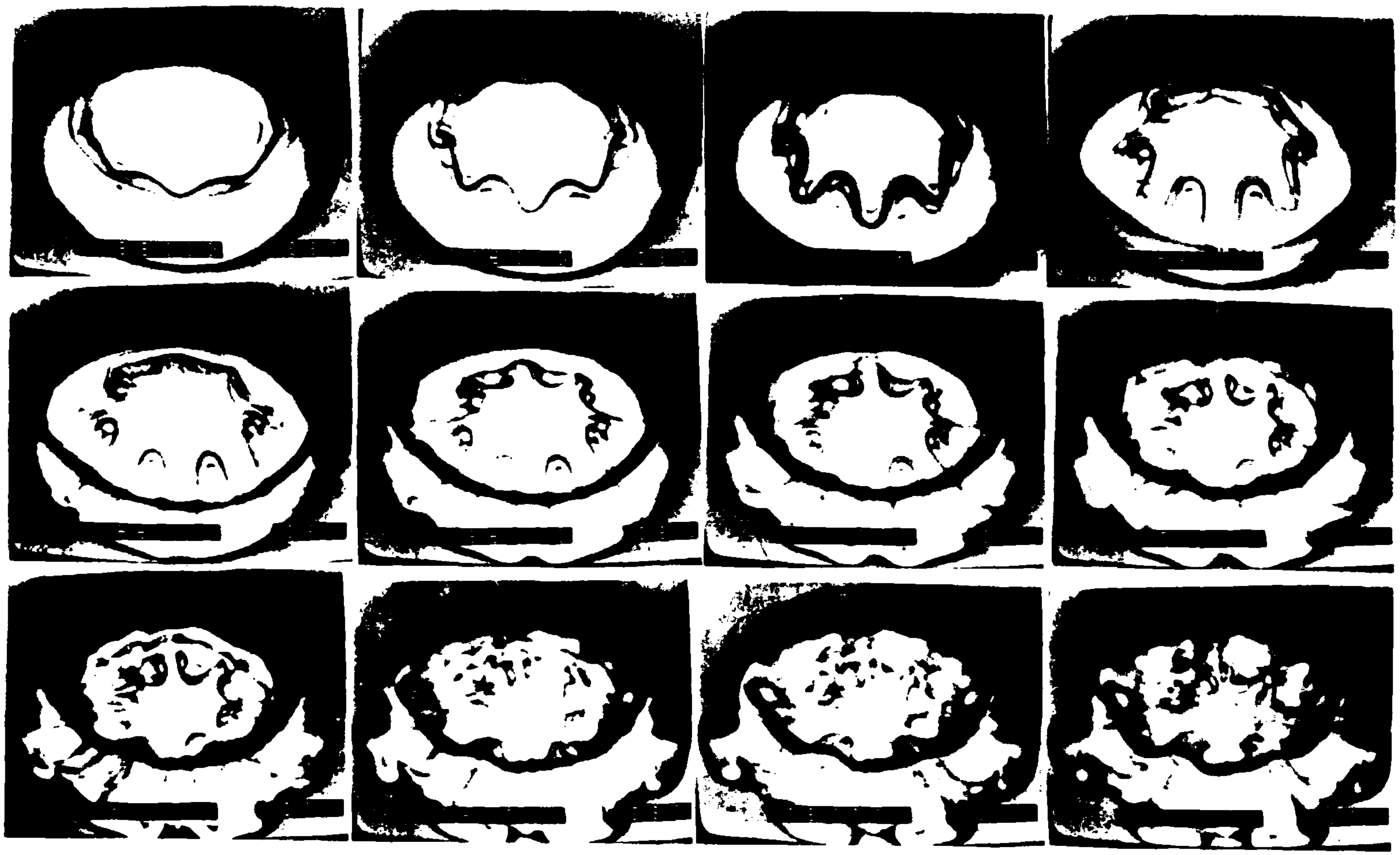


Figure 7. Development of loop structured secondary vortex (oblique plan view, dye placed on surface). Vortex ID.#51.130, Re_0=811. Pictures are 0.167 seconds apart.

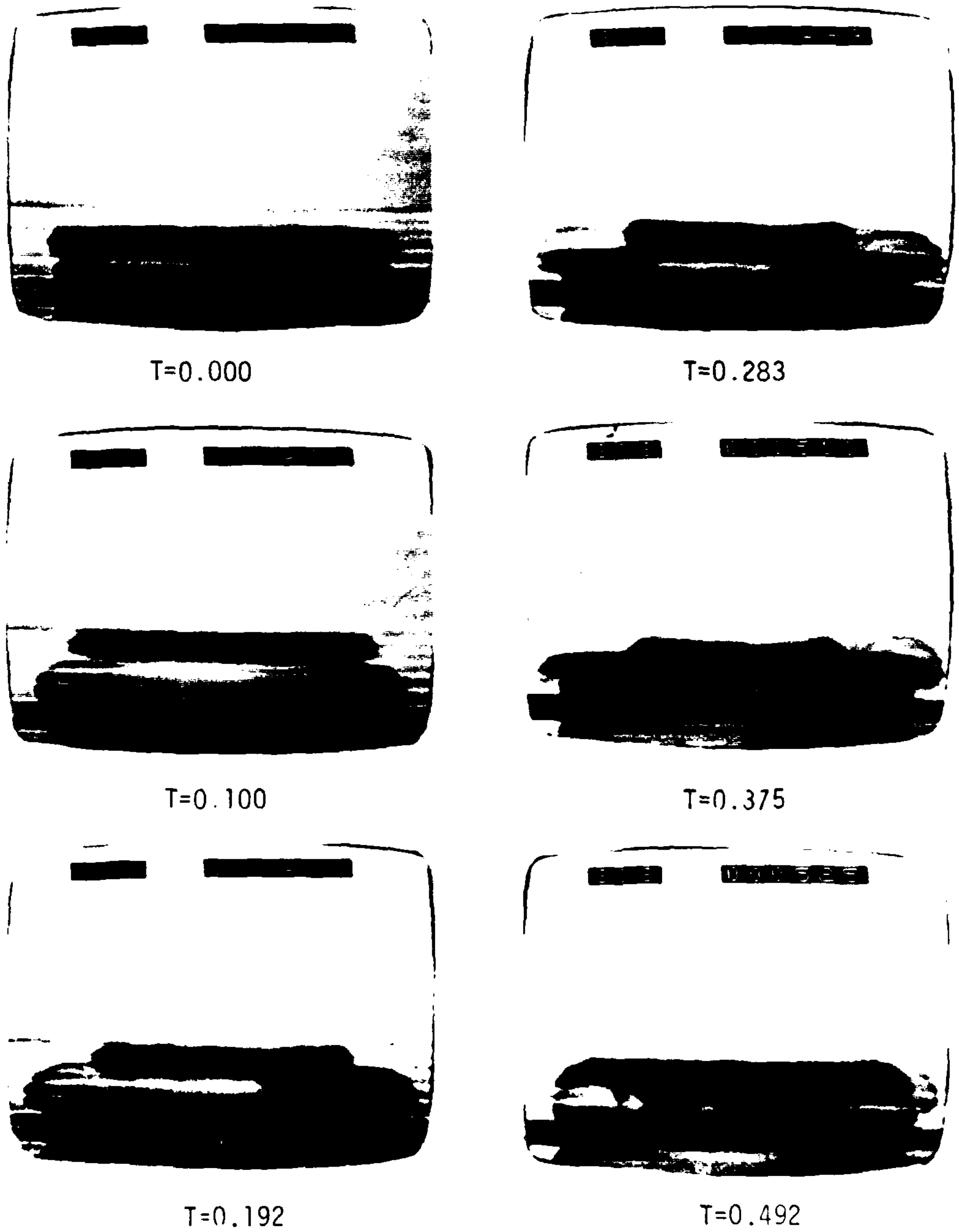
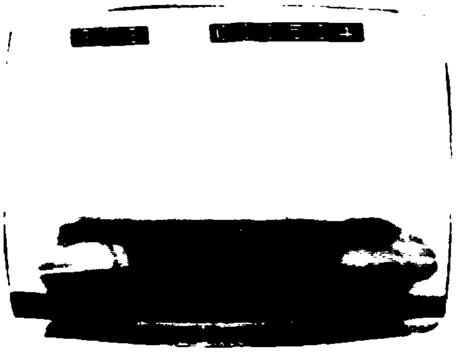
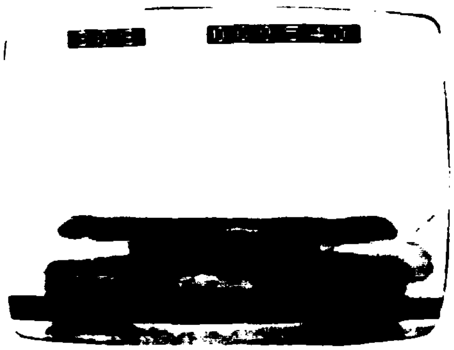


Figure 8a. Development of kink structured secondary vortex with secondary vortex ejection (side-view, dye placed on surface). Vortex ID. =52.265, Re_o=3000. Sequence continued on next page.

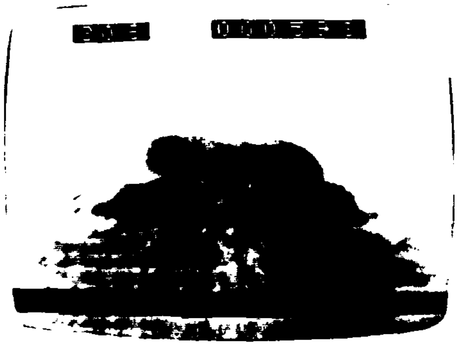


T=0.575

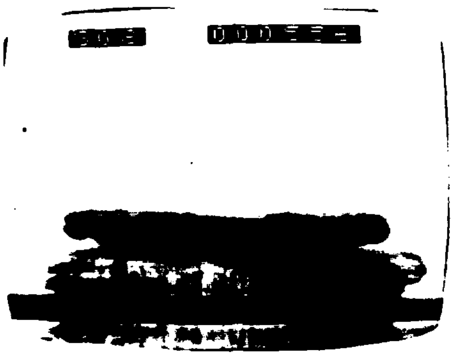
T=0.933



T=0.625



T=1.07



T=0.758

T=1.46

Figure 8b. (continued)

What is clear from this study, and confirmative of the analytical prediction discussed in Section III, is that vortices adjacent to solid boundary cause the creation of vortices of opposite sign which are instrumental in the breakdown and dissipation of the original vortex.

The second flow structure which has been widely suggested as a key mechanism in the process of turbulence generation in the wall region is the hairpin or horseshoe vortex [see, for example, Smith & Metzler, 1982]. However, the suggestion of this structure has been strongly speculative since the dynamics of this type of flow structure have never been examined in detail. To examine the actual viability of hairpin vortices as constituent structures of turbulent boundary layers, we have developed a technique for generating very consistent hairpin vortices experimentally.

Through a process of experimental serendipity it was determined that hairpin vortices can be generated by the interaction of a hemispherical protuberance with a subcritical, developing laminar boundary layer. Under the proper conditions, a hemisphere will shed hairpin vortices extremely periodically and with very repeatable characteristics, as illustrated schematically by Figure 9. In Figure 10, the head of a hairpin vortex loop as it initially develops in the wake of a hemisphere is revealed by hydrogen bubble time-lines generated with a wire oriented vertically in front of the hemisphere.

Using dye and hydrogen bubble-wire visualization in conjunction with hot-film anemometry measurements, the characteristics of the hairpin vortices have been examined over a wide range of parameters [Acarlar, 1984]. The extensive visual studies indicate that the loop formation and interaction process is very complicated and three-dimensional, developing many convoluted, yet very repeatable patterns as the hairpin vortices convect downstream. However, the type of visual pattern observed is very dependent upon the location and orientation of the bubble-wire. Figure 11 shows three examples of the different types of dual-view bubble-line patterns obtained with the bubble-wire located five radii downstream of the hemisphere and at three different heights relative to the wall.

What has been determined by this extensive study is that the visualization patterns which develop as a consequence of hairpin vortex development and that the velocity signatures they generate bear remarkable consistency with patterns and signals in the near-wall region of turbulent boundary layers. The results suggest that hairpin vortices are not only a constituent of turbulent boundary layer flow structure, but are dominant flow structures. A suggestion of how such structures evolve in conjunction with the "bursting" process is shown in Figure 12, which is from a synthesis by Smith (1984) of both the turbulence structure work and the turbulence simulation work.

In general, the experimental turbulence simulation studies have proven extremely revealing, providing methods for experimental evaluation of suggested turbulence flow structure models. This work is continuing, with the examination of more complicated experimentally generated flow structures, attempting to determine the modes of interaction which lead to the evolution of outer region turbulence.

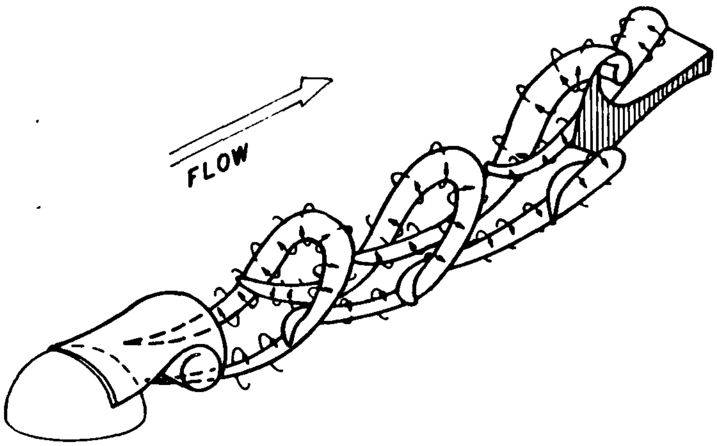


Figure 9. Schematic illustrating hair-pin vortex formation in wake of hemisphere.

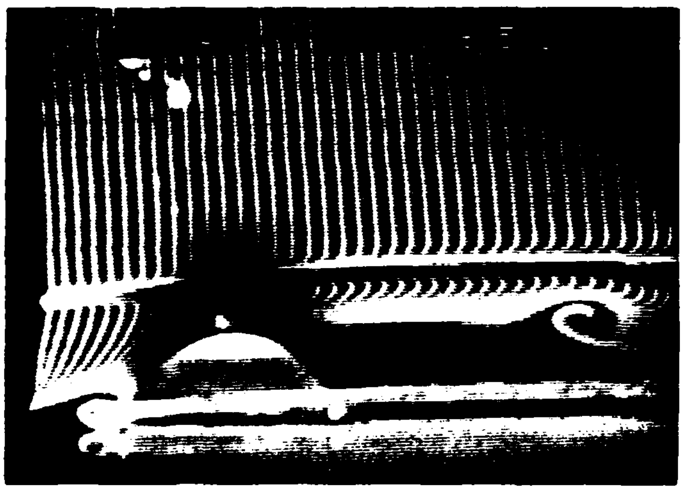
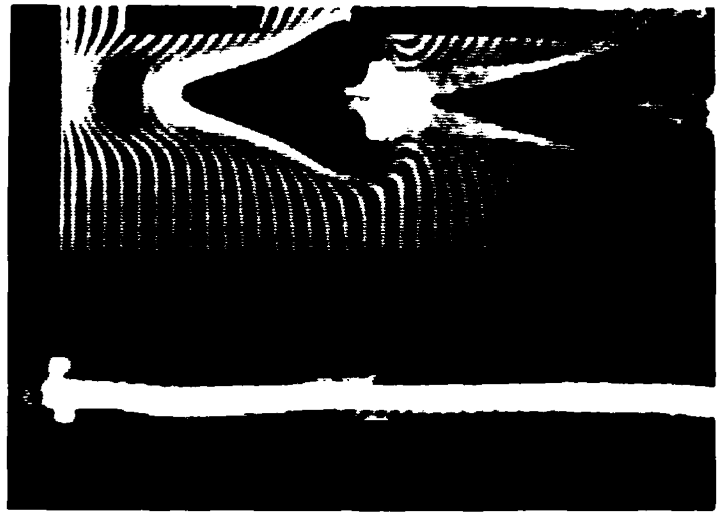
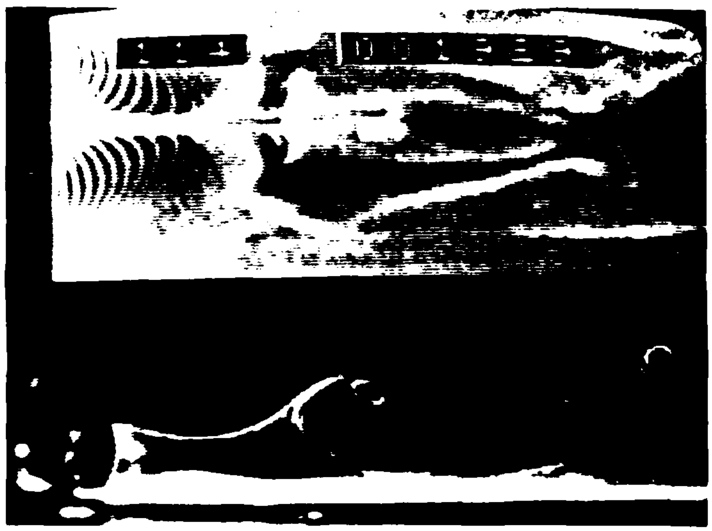


Figure 10. Side-view visualization revealing head of hair-pin vortex in wake of hemisphere.



a) $y_{wire}/R = 0.75$

b) $y_{wire}/R = 0.5$



c) $y_{wire}/R = 0.25$

Figure 11. Top-side view patterns created by hair-pin vortices with bubble-wire at $X/R = 5$ from rear of hemisphere.

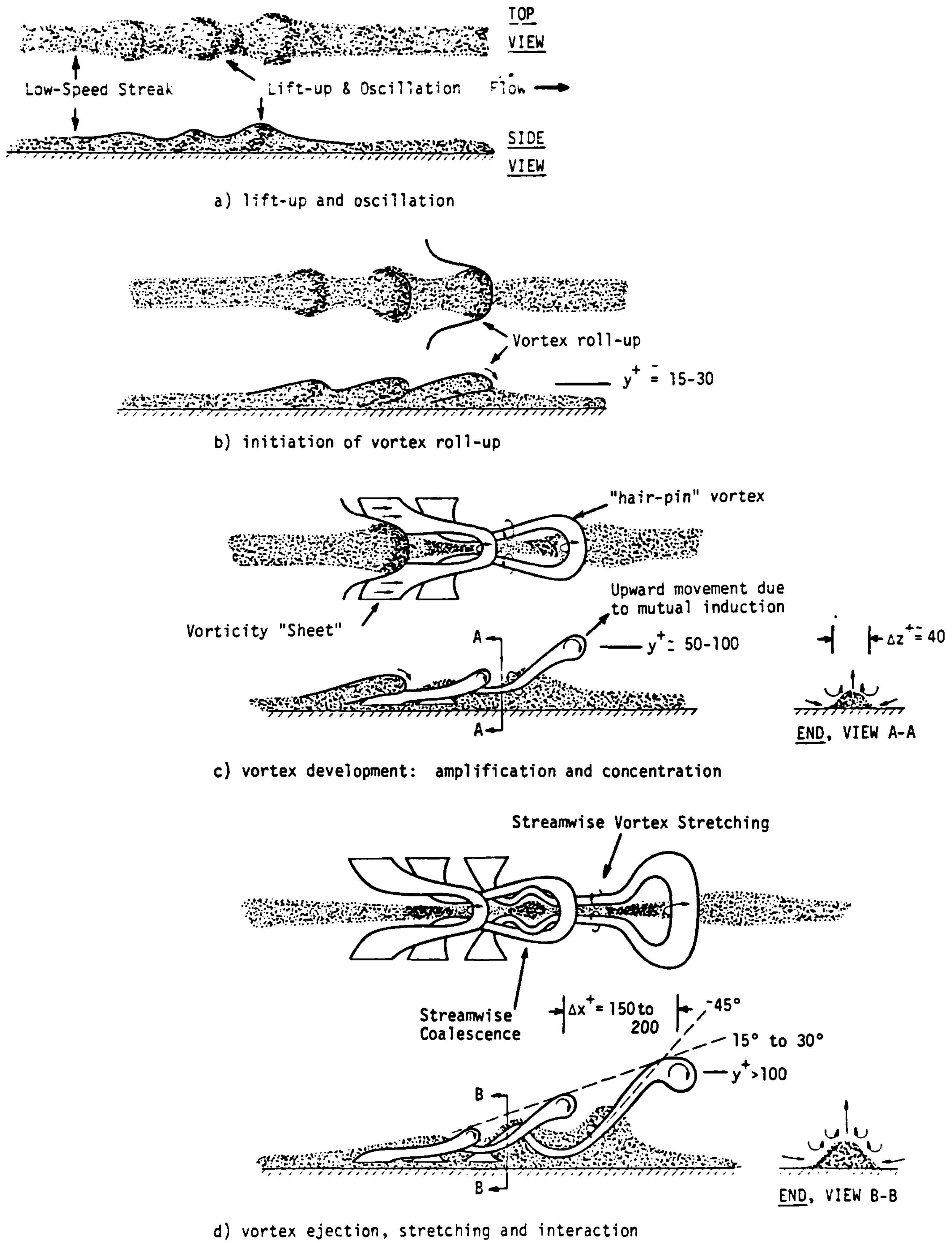


Figure 12. Illustration of the breakdown and formation of hairpin vortices during a streak "bursting" process. Low-speed "streak" regions indicated by shading.

F. Recreation of 3-D Motion

In the turbulent structure work of Smith & Schwartz (1983) described above, the dual-camera video system was used in conjunction with a fiber-optic lens to obtain combined top-end views of single realization hydrogen bubble-lines in the near-wall region of a turbulent boundary layer (see Figure 5). From these combined views, we were able to establish a number of characteristics regarding behavior in the near-wall region, particularly the characteristics and potential formation mechanism for low-speed streaks. However, the persentation of the two-view, time-sequence behavior was awkward (requiring numerous pictures). Additionally, the two-views could not be taken in true orthogonal perspective, which provoked some confusion for the unfamiliar observer.

To address the limitations of the conventional two-view visualization, a technique for compute display of the collective data of a single bubble-line sequence was developed [see Smith and Paxson (1983); Smith (1983)]. Basically, this process entails digitizing the bubble-line motion and deformation for an entire video sequence into a computer-aided display system. This was done using videographic prints of the sequence obtained with a dry copy, videographic copier. The bubble-line position information for each print in the sequence was then digitized into computer memory using a digitizing tablet. The resultant information was then computer corrected for camera viewing perspective.

Digitizing simultaneous views of the bubble-line position allowed computer reconstruction of the three-dimensional shape of the bubble-line; the input of this data for an entire sequence allowed the recreation of the "surface" traced out by the bubble-line in time and space. Figure 13 is a four-view computer generated display of the bubble-line motion and deformation for a sequence similar to Figure 5. Note that once the bubble-line position information is stored, any view from any perspective can be presented, as demonstrated by the oblique view in Figure 13. In addition, use of internal surface generation techniques in the computer allows the production of lines orthogonal to the original bubble-lines, creating a more distinct contoured surface effect as shown in Figure 14.

To further augment the capabilities of the computer-aided visualization, the reconstructed bubble-line display has been adapted for dynamic redisplay on an Evans and Sutherland dynamic display system. This latter system has been adapted to allow both 1) the recreated surface traced out by the bubble-line to be examined and viewed in any scale and from any perspective by simply rotating several interactive controls and 2) redisplay of the actual motion of the bubble-line in time and space (Smith & Paxson, 1984; Lu and Smith, 1983). In essence this allows the original motion of the bubble-line to be replayed on the computer, but from any perspective and in any selected scale. This capacity to interactively examine a flow pattern and its characteristics greatly facilitates the interpretation of the kinematics of three-dimensional flow fields, and is proving a tremendous tool for evaluation of the complex, three-dimensional bubble-line patterns created in the near-wall of turbulent boundary layers.

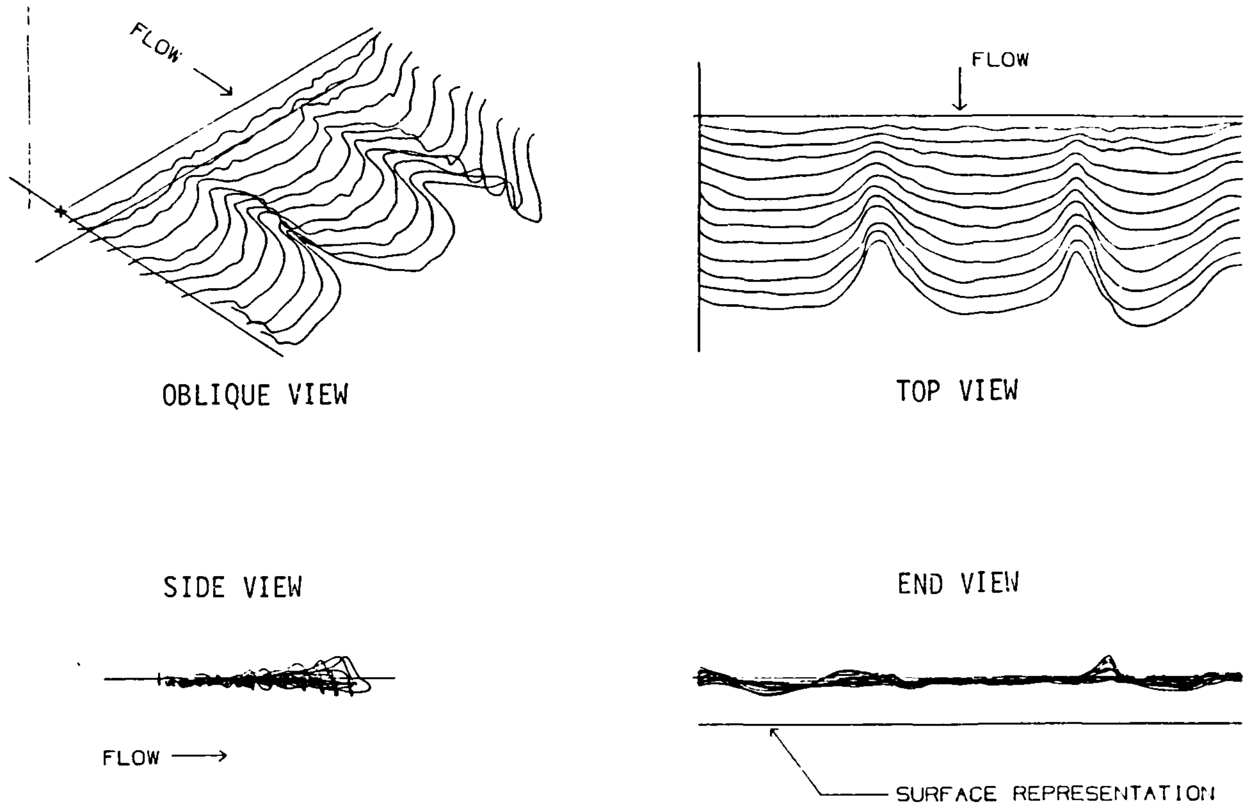


Figure 13. Computer generated orthographic and oblique-view perspective of bubble-line motion and deformation.

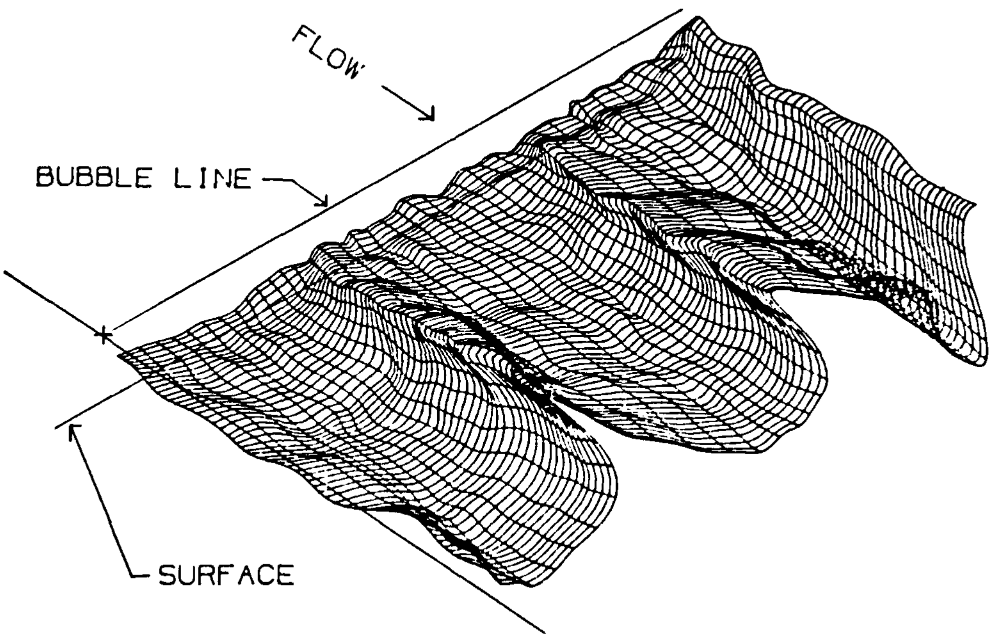


Figure 14. Oblique-view of a "contoured" surface representation of bubble-line pattern shown in Figure 13.

III. ANALYTICAL PROGRAM

A. Overview

During the five year contract period, the principle focus in the analytical program has been at obtaining a clearer understanding of the causes and effects of the cyclical and coherent events that take place within the turbulent boundary layer. The objective has been to identify particular physical mechanisms that would potentially give rise to the flow patterns observed experimentally and to explore the consequences of various analytical models. The long term goal of this approach is to develop a clear understanding of the dynamics of the turbulent boundary layer in the expectation that this understanding will ultimately lead to improved models for the turbulence quantities in the time-mean equations. In this way, prediction methods can finally be developed which are based upon the true physics of the turbulent flow. During the course of the research, when a particular aspect has appeared promising, a turbulence model in a predictive mode was attempted. The turbulent boundary layer is a double-structured layer consisting of an outer layer and an inner wall layer closest to the wall; during the contract period a rational model for the mean velocity profile in the wall layer was developed and tested against experimental data. A semi-empirical model for the outer region was also developed. Improved numerical schemes for turbulent prediction methods were also obtained and these will be discussed subsequently. At this stage however, the major thrust of the work will be described.

B. Vortex-Boundary Layer Interactions

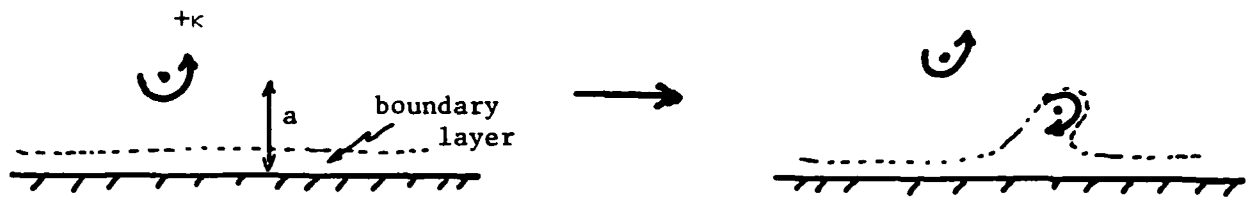
It was evident at a fairly early stage that vortex motions within the turbulent boundary layer play an important role in the dynamics of the layer. It has been suggested as early as 1973 by Corino and Brodkey that the passage of a vortex was in some way associated with a subsequent ejection (or burst) of fluid from the wall layer into the outer layer. Since it was clear that vorticular motions were an omnipresent feature of the outer layer flow, a major effort during the contract period was devoted to investigating the effect that convected vortices have on the viscous flow near walls. These studies will subsequently be discussed in more detail here, but the basic effect can be summarized as follows. When vortices are convected above a wall, an unsteady separation occurs relatively rapidly in the viscous boundary layer flow that is present near the wall; this unsteady separation develops and takes place in a frame of reference convecting with the vortex. A period of rapid and accelerating boundary layer growth ensues which is then culminated by an ejection of fluid from the boundary layer region; this event may be described as a viscous-inviscid interaction in which there is a strong interplay between the two regions. In many cases, the result of this interaction is the creation of a secondary vortex which is of opposite rotation to the parent vortex. Consequently, during this contract period, a basic physical mechanism for the production of vorticity from a wall boundary layer has been discovered and documented in the analytical and also in the experimental programs; in this mechanism convected vortices induce eruptions from the viscous wall of layer regions and produce structures similar to themselves.

In this phenomenon, there exists the clear possibility of explaining how a turbulent boundary layer is able to constantly regenerate itself through the continual introduction of new vorticity into the outer layer. The various studies on specific areas covered during the contract period will not be discussed briefly.

The first problem that was considered corresponds to the simplest physical situation where a vortex interacts with a wall boundary layer, namely a vortex of positive rotation $+\kappa$ located at a distance a above a plane wall in an otherwise stagnant fluid. Inviscid theory predicts that such a vortex will convect with constant velocity to the right and remain at constant distance above the wall as depicted schematically in figure 14(a). The boundary layer calculations reported in Walker (1978) showed that very rapidly after the initiation of the motion, a secondary eddy occurred in the boundary layer. It was conjectured that the secondary eddy would be ejected from the boundary layer; since the secondary eddy is of opposite rotation to the parent vortex which created it, it was expected that the eruption would cause the parent to rebound from the wall and slow down. The problem has direct relevance to the effect of trailing aircraft vortices on boundary layers on a landing strip and had been studied experimentally by Harvey and Perry (1971); close agreement was obtained between these experiments and the theory of Walker (1978).

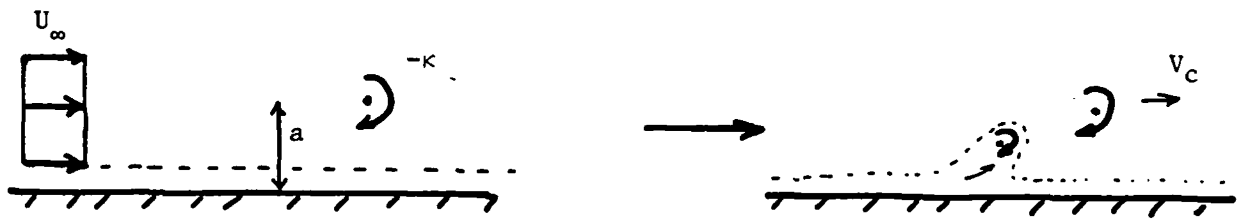
The next vortex configuration studied during the contract period is sketched in figure 15(b) and corresponds to a two-dimensional vortex of negative rotation convected in a uniform flow to the right. Flow visualization in turbulent boundary layers is often carried out in spanwise planes and reveals vortex rotations of the type depicted in figure 15(b); the vortices in the turbulent boundary layer are three-dimensional and the visualization plane actually shows a slice through the three-dimensional vortex. Nevertheless, the situation in figure 15(b) for a two-dimensional vortex was believed to be a reasonable first attempt to simulate some of the conditions in the outer region of a turbulent boundary layer. Depending on the vortex strength κ and the distance from the wall a, the vortex convects to the right at some fraction α of the uniform flow speed U_∞. A wide variety of cases in the range $0<\alpha<1$ have been considered by Doligalski and Walker (1978), Doligalski (1980) and Doligalski and Walker (1984). Numerical solutions for the boundary layer development after the initiation of the motion show a variety of unusual unsteady separation patterns that occur in the boundary layer in a frame of reference which convects with the vortex. For all α, events take place within the boundary layer which are expected to lead to an eruption of the boundary layer and subsequent creation of a secondary vortex as sketched in figure 15(b). While the bulk of the calculations in Doligalski and Walker (1984) were carried out for a rectilinear vortex, it was also argued that the results are likely to be representative of all vortex motions in two-dimensions. The similarity of the phenomena to bursting in turbulent boundary layers should be noted; here the convecting vortex induces an eruption of boundary layer fluid giving rise to an inviscid-viscous interaction and the introduction of new vorticity into the inviscid region.

In figure 15(c), a third configuration is illustrated where a uniform flow is reduced to a speed AU_∞ (where $A<1$) near the wall through a region of uniform shear. The slope of the uniform shear was selected to correspond



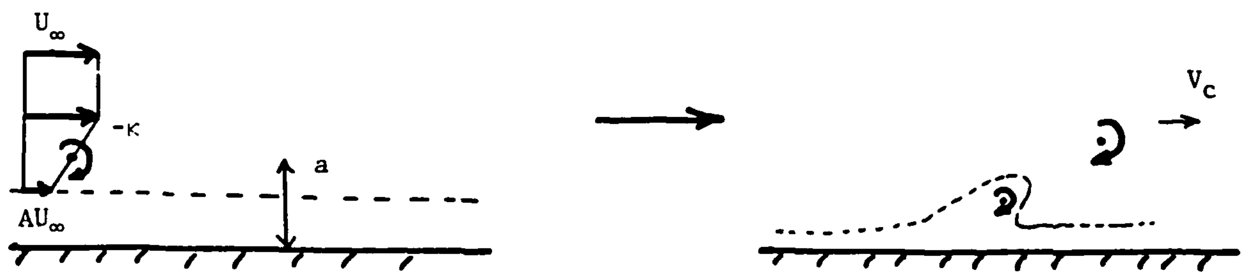
(a) Positive rotation vortex in an otherwise stagnant flow

Schematic view of subsequent boundary layer eruption



(b) Negative rotation vortex in a uniform flow

Schematic view of subsequent boundary layer eruption



(c) Negative rotation vortex in a shear flow

Schematic view of subsequent boundary layer eruption

Figure 15. Various vortex-boundary layer configurations considered in this study

with the mean pforile in the outer layer of a turbulent boundary layer for a constant pressure flow; the vortex convects to the right in the uniform shear. The idea here was to simulate the environment experienced by a convected vortex in a turbulent shear flow. The response of the boundary layer was reported by Doligalski, Smith and Walker (1980) and by Doligalski (1980). Although the situation in this case is more complicated than for the cases depicted in figure 15(b), the net result of the convected vortex is similar and leads to an eruptive boundary layer behavior behind the moving vortex. In this study (Doligalski et al., 1980) a fundamental mechanism for the production of turbulence near a wall was proposed and this is illustrated schematically in figure 16.

In the first phase of the process depicted in figure 16, a parent vortex of negative rotation is convected above the wall; downstream of the vortex at a location in the streamwise direction equal to almost twice the distance of the vortex from the wall, the boundary layer begins to respond to the vortex motion. As time passes, the upwelling fluid from the boundary layer penetrates the inviscid region to an increasing extent [figs. 16(b) and 16(c)] and as it does so, it penetrates a region of cross flow in the inviscid region. This will ultimately lead to an overturning of the erupting boundary layer fluid as indicated in figure 16(d); the process culminates in a strong inviscid-viscous interaction depicted in figure 16(e). In this, the second phase of the overall process, a vortex labelled S is spawned in the interaction. Finally, the spawned vortex will be convected to the right and may possibly interact with the original parent vortex; further interactions with the boundary layer are also expected for both vortices. In the study by Doligalski et al. (1980) the first phase of the proposed process was calculated; the third phase may be modeled (Doligalski, 1980) by simply inserting a (spawned) vortex into the flow at the expected location of viscous-inviscid interaction and then considering the subsequent interaction with the parent vortex. Reynolds stress contributions for the first and third phases of the process were evaluated by Doligalski (1980) and were found to be qualitatively similar to those measured in turbulent boundary layers. However, it is believed that the major contributions to the Reynolds stress occurs for the event on figure 16(e). Unfortunately the techniques required to compute such a strong inviscid-viscous interaction do not exist at present and this is a subject for future research.

During the contract period, the case of counter-rotating vortices was also addressed. Pairs of counter-rotating vortices are observed in a variety of physical situations and it has often been speculated by various authors that such pairs are an important feature within the turbulent flow close to a wall. When dye or hydrogen bubbles are introduced into a turbulent boundary layer near the wall, the dye is observed to collect into long and persistent streaks. It is often conjectured that the streak structure is a result of long counter-rotating vortex pairs near the wall which are aligned in the streamwise direction. At isolated locations in the streamwise and spanwise directions, the regular streak structure is observed to breakdown and a violent eruption of fluid from the inner to the outer region is observed; this is the bursting phenomenon and it sometimes suggested that the bursting is somehow connected with a supposed pair of counter-rotating vortices. Consequently, it was considered desirable to undertake a careful

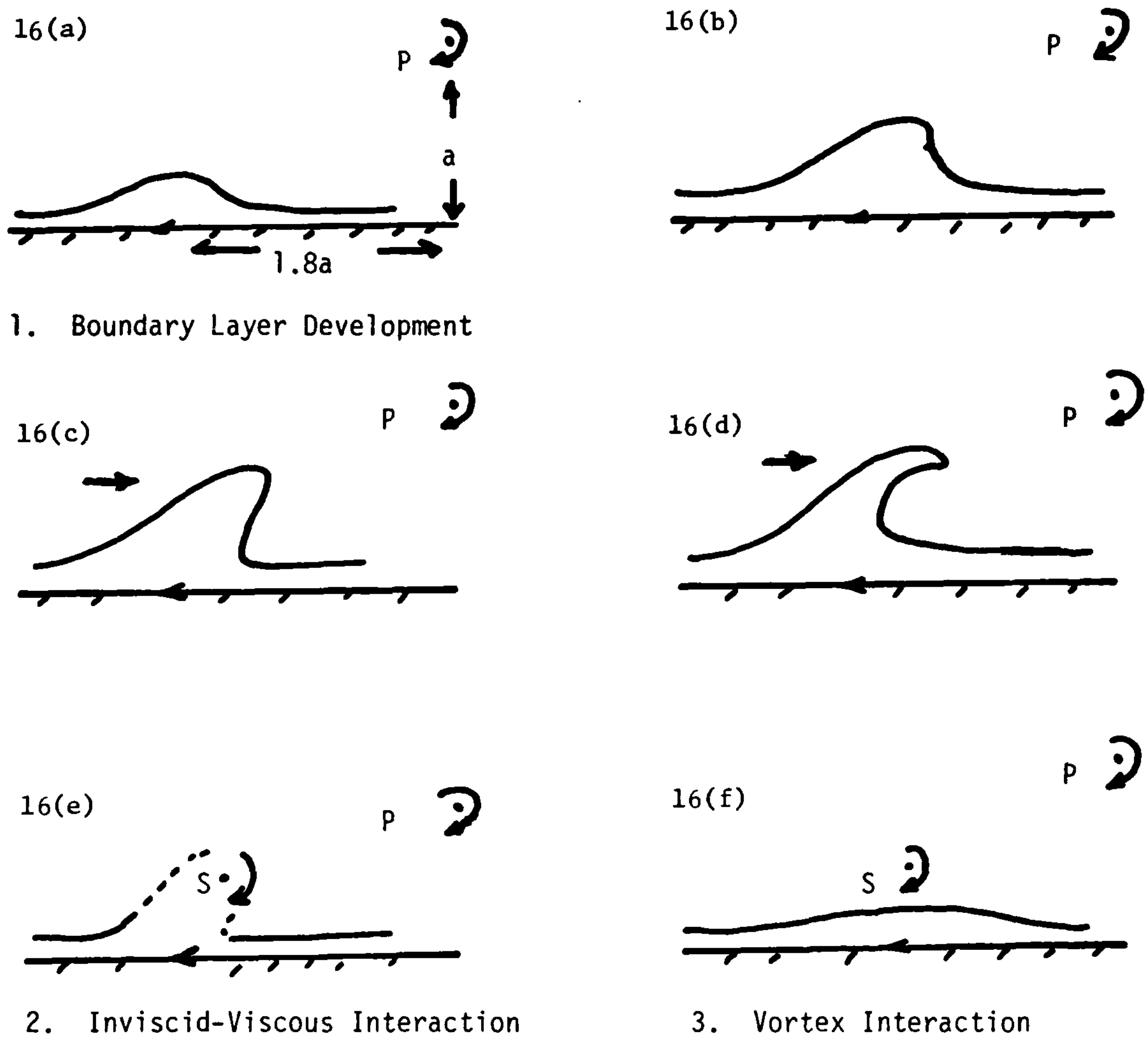
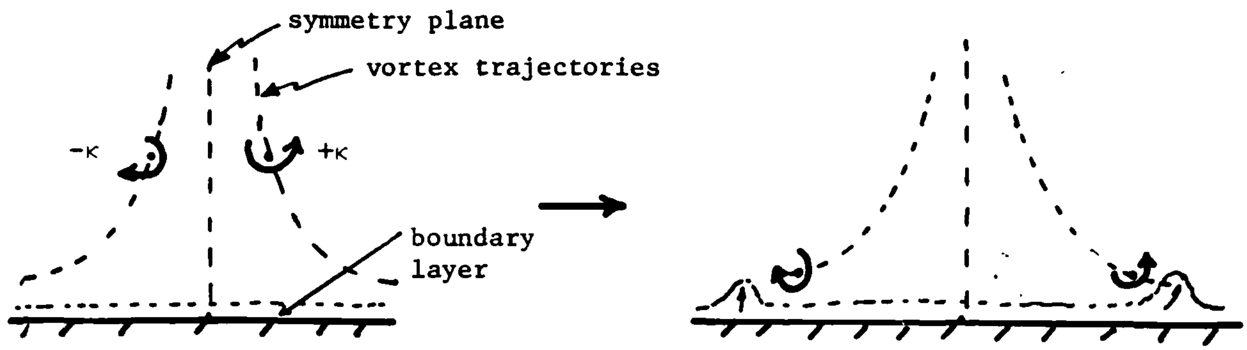


Figure 16. Sketch of proposed three phase vortex regenerative mechanism; P and S denote parent and spawned vortices, respectively

study of the boundary layer effects induced by a vortex pair and to this end both configurations indicated in figure 17 were considered. Partial results were reported by Ersoy and Walker (1983) and more complete results will appear in Ersoy (1984). The main conclusions may be summarized as follows. Depending on the assumed sense of rotation of the vortices, the pair will either move toward the wall as in figure 17(a) or recede from the wall as in figure 17(b); the vortex trajectories in these cases may be obtained as an exact solution. When the vortices move toward the wall, the production of secondary vorticity and an eruption of the boundary layer occurs very rapidly at locations outboard of the downward moving pair. On the other hand, for a pair which recede from the wall (figure 17(b)), a boundary layer eruption also occurs, but in this case near the symmetry plane inboard of the upward moving vortices. The main point here is that counter-rotating vortices produce boundary layer eruptions and the production of secondary vorticity, whether they are moving toward or away from a wall.

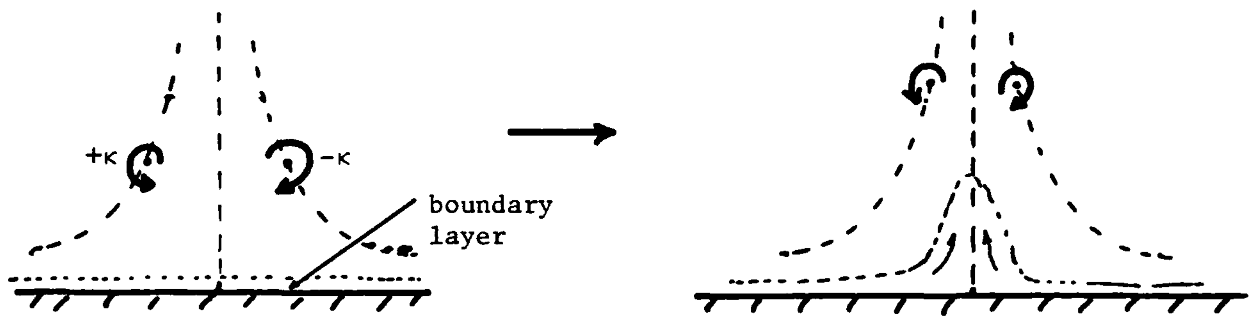
In the next phase of the contract, the effect of an inclination of the vortex pair was addressed; the geometrical configuration is depicted in figure 18. Again, depending on the sense of rotation, the vortices either recede from or approach the wall (at an angle of attack α). This portion of the work has possible relevance to problem of streak breakdown but is also of interest in connection with the motion of vortex structures in the outer layer of the turbulent boundary layer and their influence on the wall boundary layer. In an effort to explain the bursting phenomena Falco (private communication, 1982) has created vortex rings which moved toward a wall; he subsequently observed a distortion of the ring into a loop and then a complex interaction with wall boundary layer in which ejection of boundary layer fluid occurred. The situation sketched in figure 18(a) represents a simulation of the situation studied experimentally by Falco in the symmetry plane of the vortex ring. A variety of calculations have been carried out for the response of the boundary layer for various angles of attack α and for vortices moving toward and away from the wall; these calculations show a variety of unexpectedly complex boundary layer separation patterns. The detailed results will be reported in Ersoy (1984) but the main features may be summarized as follows. For the situation depicted in figure 18(a), where the vortex pair moves toward the wall, boundary layer separation and an eruption always occurs to the left of the vortex closest to the wall. The effect of the vortex furthest from the wall is much less pronounced and this vortex produces a much weaker effect to the right (of the second vortex). For a pair receding from the wall, again separation and a boundary layer eruption occurs but this time inboard (to the right) of the vortex closest to the wall.

In turbulent boundary layers, the observed vortex motions are three dimensional. The process of vortex stretching in three-dimensional flows is absent in purely two-dimensional flows and consequently it was of interest to determine the potential effects of vortex stretching on the vortex induced boundary layer eruptions discovered in this study. The first situation studied is depicted in figure 19(a) and corresponds to a vortex ring approaching a wall from above in an otherwise stagnant fluid. The trajectory of the ring was computed numerically and agreed closely with a set of companion experiments reported by Cerra and Smith (1983). As the ring moves toward the wall it stretches and the ring enlarges as depicted in figure 19(a). In the numerical calculations reported by Doligalski (1980) for the boundary



(a) Downward moving pair

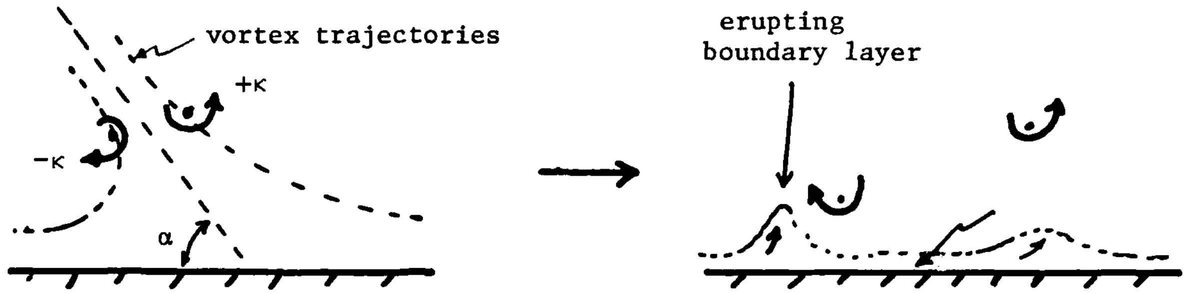
Schematic view of subsequent boundary layer eruption



(a) Upward moving pair

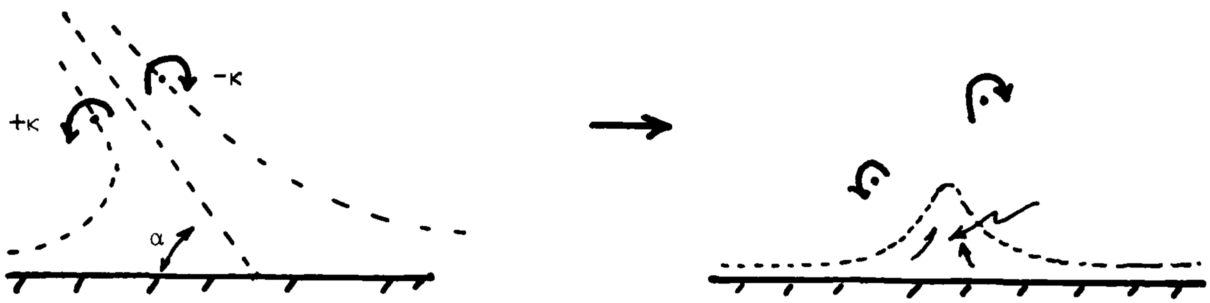
Schematic view of subsequent boundary layer eruption

Figure 17. Symmetric counter-rotating vortex pair configurations considered in this study



(a) Vortex pair approaching a wall obliquely

Schematic view of the subsequent boundary layer eruption



(b) Vortex pair receding from a wall obliquely

Schematic view of the subsequent boundary layer eruption

Figure 18. Vortex pair approaching (and receding) from a wall at an angle of attack

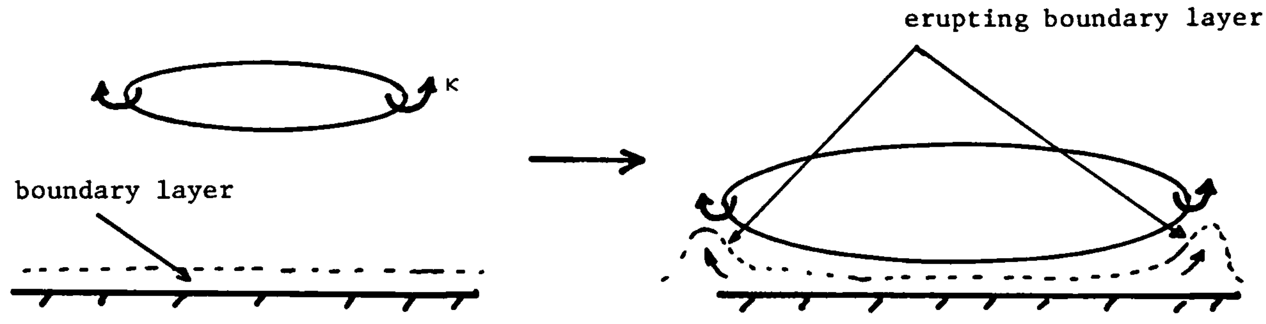
layer induced by the downward moving ring, secondary eddies were observed very rapidly as the ring approached the wall. In fact, it was concluded that the process of vortex stretching intensifies the basic vortex induced boundary layer eruption effect observed in two-dimensions. The experiments of Cerra & Smith (1983) confirm the theoretical results and show a variety of strong eruptions which culminate in the ejection of a secondary vortex ring from the boundary layer regions.

In the final portion of the contract period, the analytical program has been directed at the calculation of fully three-dimensional convected vortex loops. The basic configuration is sketched in figure 19(b) where the calculation is initiated by inserting a vortex ring at angle of attack into a uniform flow above a wall. The subsequent trajectory of the vortex is calculated by carrying out a complicated integration of the Biot-Savart integral. It emerges that the ring distorts into a loop and in the situation depicted in figure 19(b) enlarges and moves toward the wall. The effect of this type of structure on the wall boundary layer is again eruptive and some results will be reported in Ersoy (1984).

C. Turbulence Modeling

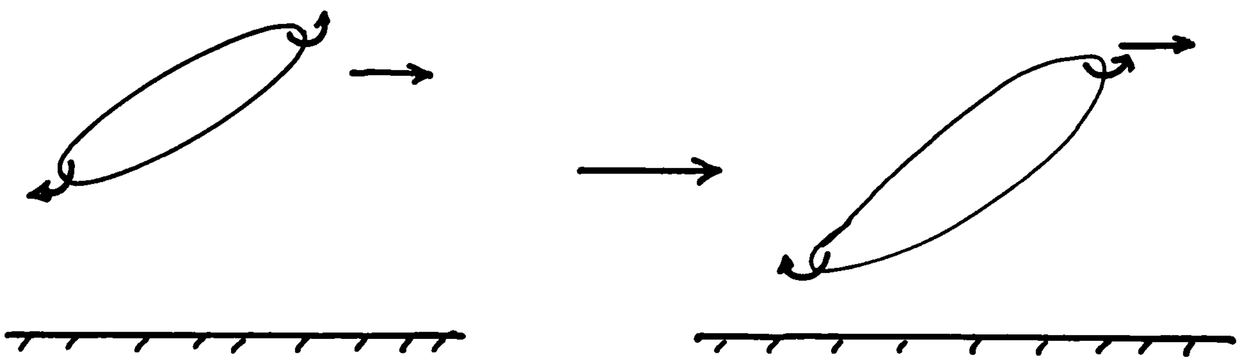
In previous years, a model for the mean profile had been developed (Walker and Scharnhorst, 1978, Scharnhorst 1978) for the wall layer. This model for the wall layer was based upon the observed coherent behavior of the wall layer which is as follows: If a fixed region in the spanwise and streamwise directions is observed for a period of time near the wall, the wall layer will be in the quiescent state for a large majority of the total observation time. During the quiescent period, the wall layer streaks are observed and there is little interaction between the wall layer and the outer layer of the turbulent boundary layer. During this period, the inner wall layer responds to motions in the outer layer in an essentially passive way. The relatively ordered flow in the wall layer terminates at isolated locations in the streamwise and spanwise directions with the bursting process in which fluid is ejected from the inner layer into the outer layer. In the bursting event there is a strong interaction between the two layers but the event is of relatively short duration. The wall layer streaks are quickly re-established and another quiescent period occurs. The entire process repeats cyclically but not periodically. Using these observed flow features as well as the observed length scales, it is possible to show that the equations governing the time-dependent velocities in the wall layer are linear and of the heat conduction type. By considering all possible similarity solutions of these equations and taking a time average over a typical quiescent period, an analytical model was produced for the mean profile. This analytical model profile was compared extensively with experimental data and good agreement was obtained.

The wall layer model is an approximate representation of the mean velocity profile in the sense that any contribution to the mean profile made during the bursting event is neglected; this is on the grounds that the event is of relatively short duration with respect to the quiescent periodic contributions. In order to obtain a turbulence model for the outer layer it is necessary to model instantaneous contributions to the Reynolds stress. This is the long term goal of the studies of vortex dynamics carried out in



(a) Axisymmetric ring approaching a wall

Schematic view of the subsequent boundary layer eruption



(b) Vortex ring approaching a wall

Subsequent distortion into a vortex loop

Figure 19. Vortex rings (and loops) approaching a wall

this contract; the objectives lie in clearly defining what physical mechanism causes the bursting, then in modeling the process and finally in performing suitable time-averages to obtain a Reynolds stress model. This goal is long term and in the present contract it was considered desirable to at least put the wall layer model into a predictive mode; for this, a temporary model is required for the outer layer and to this end a simple eddy viscosity model was adopted. A procedure was developed (Yuhas and Walker, 1983) wherein the two basic parameters in the eddy viscosity model could be correlated for various effects using measured velocity profile data. An optimization computer code was developed to carry out the data comparisons and the method was applied to flows with pressure gradients and flows with mainstream turbulence. As an illustration of how well the velocity profiles match, typical data (taken under an experimental program at United Technologies Research Center in East Hartford, Conn.) for mainstream turbulence levels ranging from 3.5% to 6.5% are illustrated in figure 20 for a zero pressure gradient flow. These mainstream turbulence levels are typical for boundary layer flows in a gas turbine. It may be seen that the analytical profiles computed in the optimization procedure represent the measured data very well. From these optimization studies, it proved possible to correlate a single parameter K in the eddy viscosity formula to account for mainstream turbulence effects. A quadratic correlation is illustrated in figure 21 and this correlation may in principle be used in a prediction method as a simple way for accounting for the effects of mainstream turbulence.

D. Numerical Methods

During the course of the work in developing prediction methods, it became desirable to attempt to develop improved numerical procedures for the type of parabolic equations encountered in boundary layer problems. New second order methods for parabolic equations were developed (Lee and Walker, 1982) and some typical results are illustrated in figure 22 where the root-mean-square errors for two new calculation methods are compared with that associated with two existing methods (the Keller Box Method and the classical Crank-Nicolson method). The example problem for which the error is illustrated in figure 22 is the Howarth laminar boundary layer problem; this flow is a boundary layer developing in an adverse pressure gradient. The boundary layer originates at $\xi = 0$ and a separation point is predicted at $\xi \cong 0.90$; the error plotted in figure 22 is the average error incurred at each ξ station in a boundary layer integration initiated at $\xi = 0$. It may be observed that the new methods offer a good increase in accuracy. It is worthwhile to note that it was demonstrated in the study of Lee and Walker (1982) how differencing techniques developed for ordinary differential equations could be carried over with some additional effort to parabolic partial differential equations. This aspect of the study has been advanced with the development of new fourth order methods for linear and non-linear boundary value problems (Bogucz and Walker, 1983). The results of this latest study are very encouraging and show methods in which the number of mesh points may be reduced by two orders of magnitude as compared to a second order method.

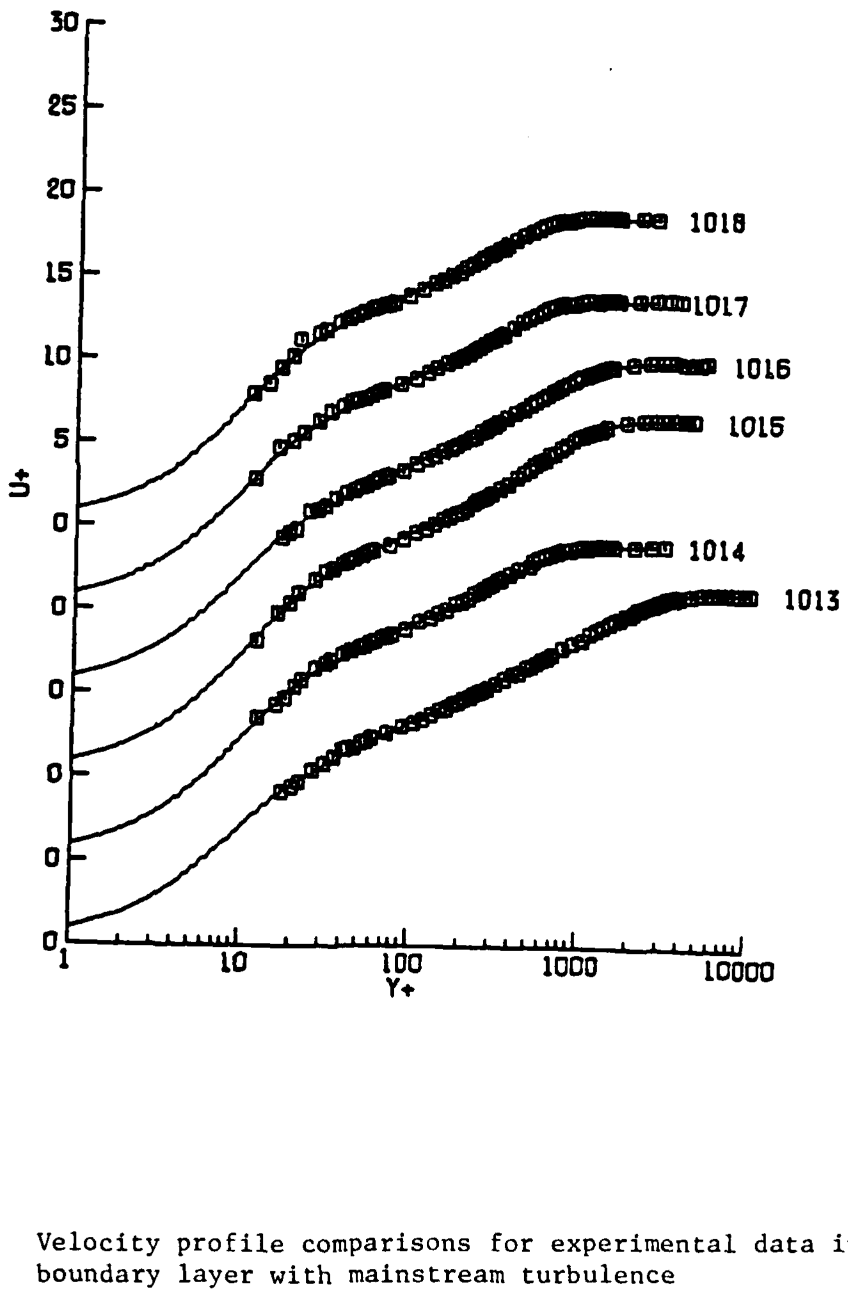


Figure 20. Velocity profile comparisons for experimental data in a boundary layer with mainstream turbulence

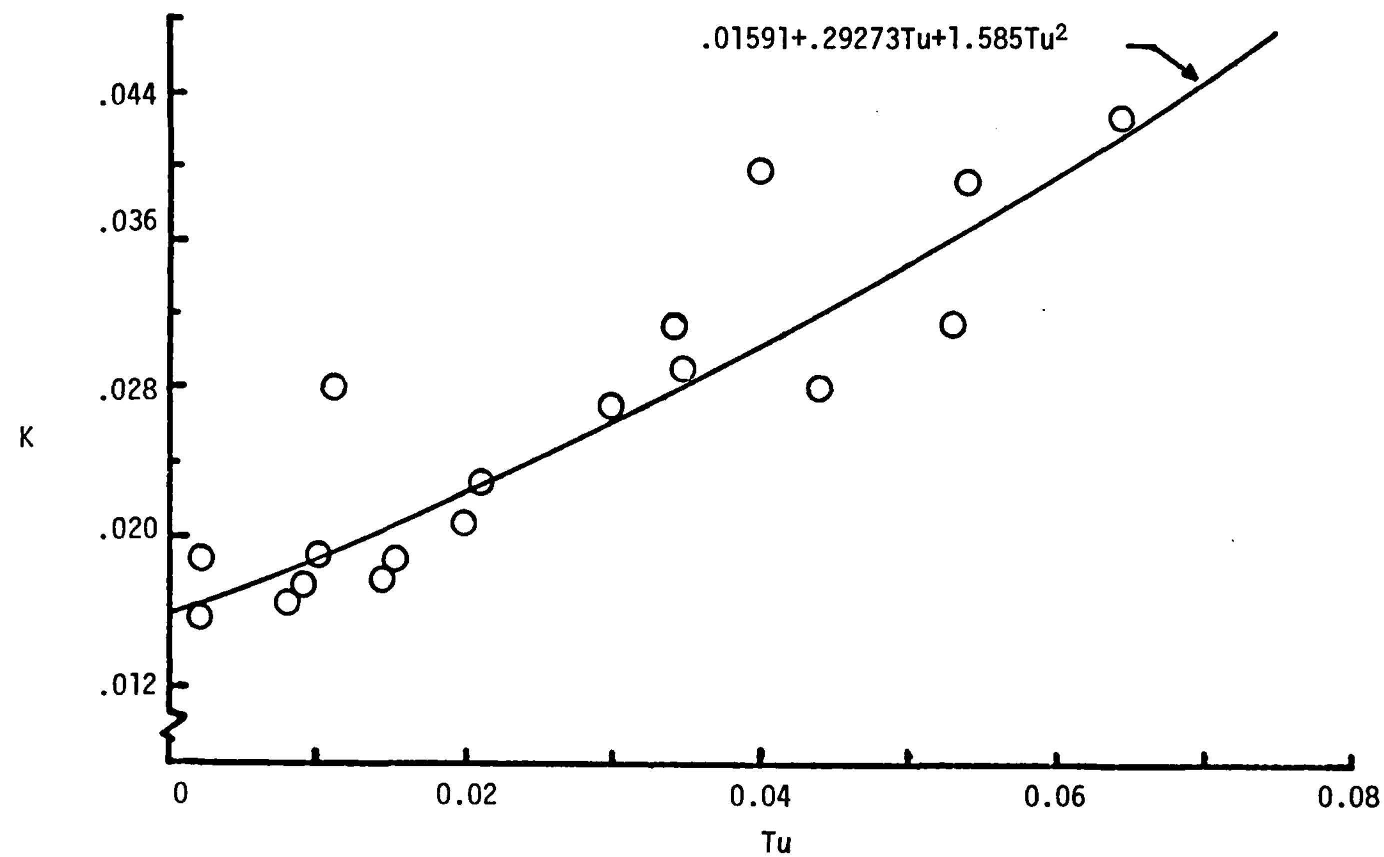


Figure 21. K parameter correlation obtained from one parameter fits of the composite similarity profile to constant pressure test data with mainstream turbulence.

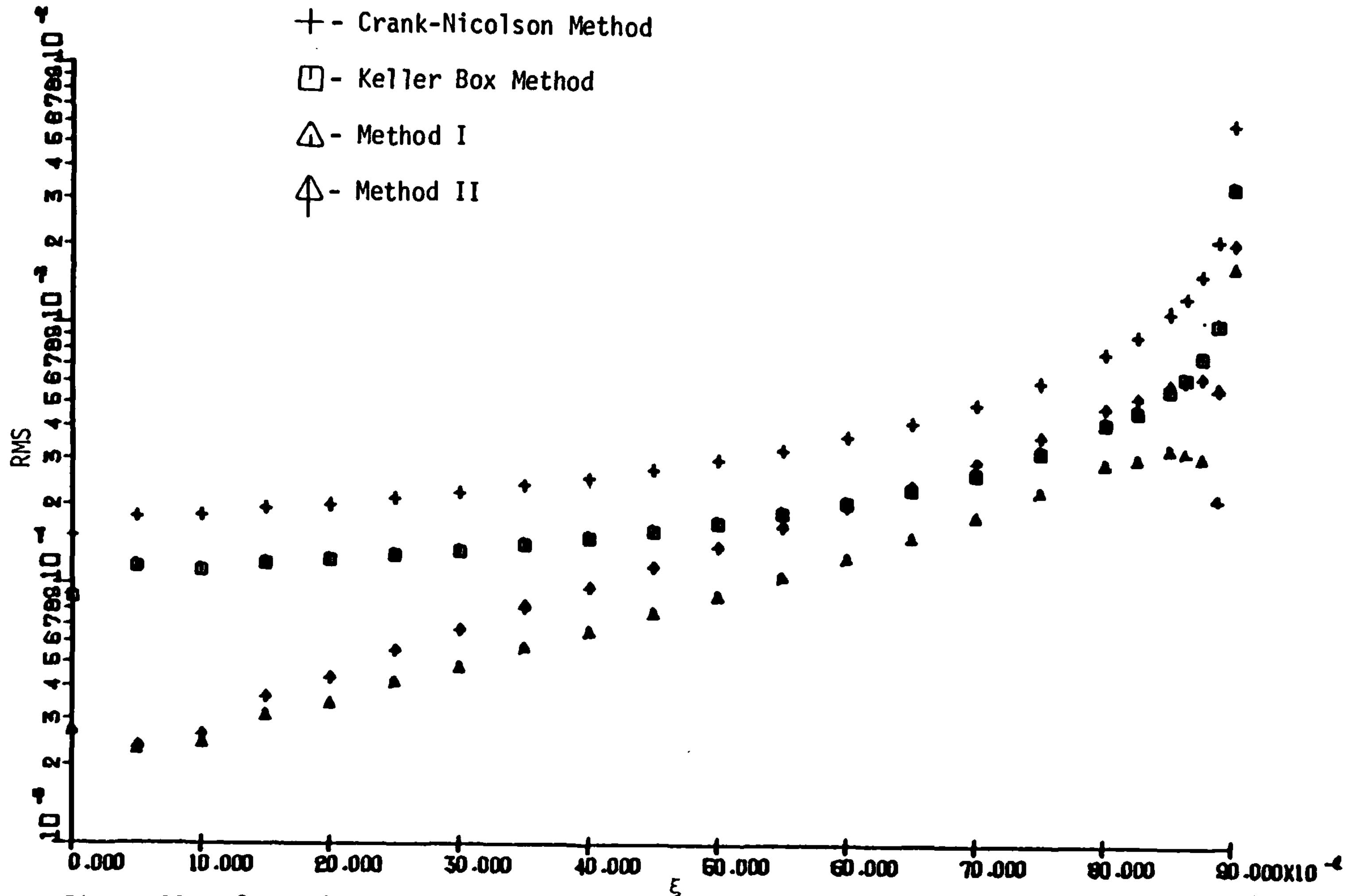


Figure 22. Comparison of RMS error for the Howarth flow problem

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27. Walker, J.D.A. 1978 Proc. Roy. Soc. Lond. A, 359, 167-188.

28. Walker, J.D.A. & Scharnhorst, R.K. 1977 "Solutions of the Time-Dependent Wall Layer Flow in a Turbulent Boundary Layer" in Recent Advances in Engineering Science, G.S. Sih, editor, Lehigh University Press.

29. Yuhas, L.J. and Walker, J.D.A. 1982 "An Optimization Technique for the Development of Two-Dimensional Steady Turbulent Boundary Layer Models", Technical report FM-1, also AFOSR-TR-82-0417, Department of Mechanical Engineering and Mechanics, Lehigh University.

V. ASSOCIATED PUBLICATIONS, PRESENTATIONS AND THESES

A. PUBLICATIONS

[1] Walker, J.D.A., "The Boundary Layer Due to Rectilinear Vortex", Proc. R. Soc. Lond. A., Vol. 359, 1978, pp. 167-188.

[2] Doligalski, T.L. and Walker, J.D.A., "Shear Layer Breakdown Due to Vortex Motion," Proceedings of the AFOSR Workshop on Coherent Structure of Turbulent Boundary Layers, C. Smith and D. Abbott, eds., Lehigh University, November, 1978, pp. 288-339.

[3] Smith, C.R., Brown, J.J. and Crosen, D.A., "Hydrogen Bubble-Wire Simulation of a Transverse Vortex in a Turbulent Boundary Layer," Technical Report CFMTR-78-2, School of Mechanical Engineering, Purdue University, April 1978.

[4] Smith, C.R., "Visualization of Turbulent Boundary-Layer Structure Using a Moving Hydrogen Bubble-Wire Probe," Proceedings of the Workshop on Coherent Structure of Turbulent Boundary Layers, Lehigh University, May, 1978.

[5] Smith, C.R. and Abbott, D.E., Proceedings of Workshop on Coherent Structure of Turbulent Boundary Layers, Lehigh University, November 1978, pp.

[6] Doligalski, T.L., Smith, C.R. and Walker, J.D.A., "A Production Mechanism for Turbulent Boundary Layer Flows", presented at the "Symposium on Viscous Drag Reduction", Progress in Astronautics and Aeronautics, Vol. 72, G.R. Hough, ed., 1980, pp. 47-71.

[7] Smith, C.R., Schwartz, Metzler, S.P., and Cerra, A.W., "Video Flow Visualization of Turbulent Boundary Layer Streak Structure", in Flow Visualization II, W. Merzkirch, ed., Hemisphere Pub. Co., Washington, D.C., 1981.

[8] Smith, C.R., "Flow Visualization Using High-Speed Videography," Photomethods, Vol. 24, No. 11, November, 1981, pp. 49-54.

[9] Yuhas, L.J. and Walker, J.D.A., "An Optimization Technique for the Development of Two-Dimensional Steady Turbulent Boundary Layer Models," Technical Report FM-82-1, Dept. of Mechanical Engineering and Mechanics, Lehigh University, March 1982; also AFOSR-TR-82-0417.

[10] Lee, W.V. and Walker, J.D.A., "Two Improved Methods for Parabolic Partial Differential Equations", Technical Report FM-2, Department of Mechanical Engineering and Mechanics, Lehigh University, April, 1982; also AFOSR-TR-82-1034.

[11] Smith, C.R. and Metzler, S.P., "A Visual Study of the Characteristics, Formation, and Regeneration of Turbulent Boundary Layer Streaks," Developments in Theoretical and Applied Mechanics, Vol. XI, Chung, T.J. and Karr, G.R., eds., University of Alabama in Huntsville, April 1982, pp. 533-544.

[12] Ersoy, S. and Walker, J.D.A., "The Boundary Layer Induced by Counter-Rotating Vortices, in Computational and Asymptotic Methods for Boundary and Interior Layers, Proceedings of BAIL Conference, J.J.H. Miller, ed., Boole Press, Dublin, pp. 222-230, 1982.

[13] Smith, C.R. and Schwartz, S.P., "Observation of Streamwise Vortices in the Near-Wall Region of a Turbulent Boundary Layer," Physics of Fluids, Vol. 26(3), March 1983, pp. 641-652.

[14] Smith, C.R., "Application of High-Speed Videography for Study of Complex, Three-Dimensional Water Flows," Proceedings of the 15th International Congress on High-Speed Photography and Photonics, International Society for Optical Engineering, April 1983, pp. 345-353.

[15] Johansen, J.B. and Smith, C.R., "The Effects of Cylindrical Surface Modifications on Turbulent Boundary Layers", with J.B. Johansen, Report FM-3, Dept. of M.E./Mech., Lehigh University, April 1983; to appear as AFOSR Technical report.

[16] Smith, C.R. and Metzler, S.P., "The Characteristics of Low-Speed Streaks in the Near-Wall Region of a Turbulent Boundary Layer," Journal of Fluid Mechanics, Vol. 129, May 1983, pp. 27-54.

[17] Smith, C.R. and Paxson, R.D., "A Technique for Evaluation of Three-Dimensional Behavior in Turbulent Boundary Layers Using Computer Augmented Hydrogen Bubble-Wire Flow Visualization", Experiments in Fluids, Vol. 1, June 1983, pp. 43-49.

[18] Cerra, A.W. and Smith, C.R., "Experimental Observation of Vortex Ring Interaction with Fluid Adjacent to a Surface", Report FM-4, Dept. of M.E./Mech., Lehigh University, October 1983; to appear as AFOSR technical report.

[19] Bogucz, E.A. and Walker, J.D.A., "Fourth Order Methods for Two Point Boundary Value Problems", Institute of Math Applics J. Numerical Analysis, in press.

[20] Doligalski, T.L. and Walker, J.D.A., "The Boundary Layer Due to a Convected Two-Dimensional Vortex", Journal of Fluid Mechanics, in press.

[21] Smith, C.R. and Paxson, R.D., "Computer Augmented Hydrogen Bubble-Wire Flow Visualization of Turbulent Boundary Layers", in Flow Visualization III, W.J. Yang, ed., Hemisphere Pub. Co., Washington, D.C., 1984 (in press).

[22] Smith, C.R., "A Synthesized Model of the Near-Wall Behavior in Turbulent Boundary Layers", in Proceedings of Eighth Symposiums on Turbulence, G.K. Patterson and J.L. Zakin, eds., University of Missouri-Rolla, 1984 (in press).

[23] Wei, T. and Smith, C.R., "Secondary Vortices in the Wake of Circular Cylinders", under review, J. Fluid Mech.

B. PRESENTATIONS

J.D.A. WALKER

1. "Shear Layer Breakdown Due to Vortex Motion", AFOSR Workshop on Coherent Structure of Turbulent Boundary Layers, Bethlehem, PA, May, 1978.

2. "Survey of Analytical and Experimental Investigation of the Coherent Structure of Turbulent Boundary Layers", invited seminar, United Technologies Research Center, East Hartford, Connecticut, June, 1978.

3. "The Effect of Vortex Motion on Wall Boundary Layers", First Annual Specialists Workshop on Coherent Structure of Turbulent Boundary Layers, Stanford, California, July 24, 1978.

4. "Some Aspects of Turbulent Boundary Layer Separation", SQUID Colloquium on Turbulent Flow Separation, Southern Methodist University, July 19, 1979.

5. "Boundary Layer Eruptions Induced by Vortex Motion", Second Annual Specialists Workshop on Coherent Structure of Turbulent Boundary Layers, East Lansing, Michigan, July 29, 1979.

6. "A Production Mechanism for Turbulent Boundary Layer Flows", Symposium on Viscous Drag Reduction, Dallas, Texas, November 7, 1979.

7. "The Boundary Layer Due to a Vortex Convected in a Shear Flow", 32nd Annual Meeting, Division of Fluid Dynamics, American Physical Society, Notre Dame, Indiana, November 18, 1979.

8. "Vortex Wall Interactions", invited seminar, The Ohio State University, Columbus, Ohio, May 30, 1980.

9. "Boundary Layer Due to an Impacting Vortex Ring", 33rd Annual Meeting, Division of Fluid Dynamics, American Physical Society, Cornell U., Ithaca, N.Y., 23 November 1980.

10. "Boundary Layer Flow Due to a Pair of Counter-Rotating Vortices", 34th Annual Meeting, Division of Fluid Dynamics, American Physical Society, Naval Postgraduate School, Monterey, CA, Nov. 1981.

11. "The Boundary Layer Due to a Vortex Pair", BAIL II Conference (Boundary and Interior Layers - Computational and Asymptotic Methods), Trinity College, Dublin, Ireland, June 1982.

12. "Simulation of the Effects of Convected Loop Vortices", 36th Annual Meeting, Division of Fluid Dynamics, American Physical Society, University of Houston, Nov. 20-22, 1983.

C.R. SMITH

1. "Visualization of Turbulent Boundary-Layer Structure Using a Moving Hydrogen Bubble-Wire Probe", Workshop on Coherent Structure of Turbulent Boundary Layers, Bethlehem, Pennsylvania, May 1978.

2. "Visualization of Coherent Turbulence Structure Using Conventional Video Technique", First Annual Specialists Workshop on Coherent Structure of Turbulent Boundary Layers, Stanford, California, July 24, 1978.

3. "High-Speed Video Analysis of Flow Visualized Turbulence Structure", Second Annual Specialists Workshop on Coherent Structure of Turbulent Boundary Layers, East Lansing, Michigan, July 28, 1979.

4. "The Visualization of Localized, Convected Fluid Pockets in the Wall Region of a Turbulent Boundary Layer", 31st Annual Meeting, Division of Fluid Dynamics, American Physical Society, Los Angeles, California, November, 1978.

5. "Visualization of Turbulent Boundary-Layer Structure Using a Moving Hydrogen Bubble-Wire Probe and a T.V. Viewing System", invited seminar, Penn State Department of Mechanical Engineering, May 3, 1979.

6. "A Production Mechanism for Turbulent Boundary Layer Flows", Symposium on Viscous Drag Reduction, Dallas, Texas, November 7, 1979.

7. "Streak Formation in Turbulent Boundary Layers: Recent Observations", 32nd Annual Meeting, Division of Fluid Dynamics, American Physical Society, Notre Dame, Indiana, November 1979.

8. "Experimental Observation of Vortex Loop-Boundary Layer Interactions", 32nd Annual Meeting, Division of Fluid Dynamics, American Physical Society, Notre Dame, Indiana, November 1979.

9. "Video Flow Visualization of Coherent Structures in a Turbulent Boundary Layer", invited seminar, University of Maryland Fluid Mechanics Seminar Series, 7 March 1980.

10. "The Presence of Axial Vortices in Turbulent Boundary Layers: A Visual Study", invited talk, Ohio State University Colloquium on Turbulent Boundary Layer Structure, 21-23 March, 1980.

11. "Flow Visualization Results in the Near-Wall Region of a Turbulent Boundary Layer", Applied Mechanics Seminar, University of Southern California, Los Angeles, CA., July 17, 1980.

12. "Video Flow Visualization of Turbulent Boundary Layer Flows", International Symposium on Flow Visualization, Bochum, W. Germany, September 11, 1980.

13. & 14. "Flow Visualization Using High Speed Video Techniques", Invited seminars at Max-Planck Institute, Gottingen, W. Germany, September 15, 1980 and at University of Lercester, England, September 18, 1980.

15. "Effects of Reynolds Number and Surface Modifications on Streak Spacing in Turbulent Boundary Layers", 33rd Annual Meeting, Division of Fluid Dynamics, APS, Ithaca, N.Y., 23 November 1980.

16. "Experimental Observation of the Interaction of a Vortex Ring With a Flat Plate", 33rd Annual Meeting, Division of Fluid Dynamics, APS, Ithaca, N.Y., 23 November 1980.

17. "The Appearance of Axial Vortices in Vortex Shedding From a Cylinder", 33rd Annual Meeting, Division of Fluid Dynamics, APS, Ithaca, N.Y., 23 November 1980.

18. "Effects of Surface Modifications on Turbulent Boundary Layer Structure", Invited seminar NASA Langley Research Center, Virginia, 18 December 1980.

19. "The Characteristics of Low-Speed Streaks in the Near-Wall Region of a Turbulent Boundary Layer", 34th Annual Meeting, Division of Fluid Dynamics, APS, Monterey, Calif., 22 November 1981.

20. "A Visual Study of the Characteristics, Formation, and Regeneration of Turbulent Boundary Layer Streaks", Invited Paper, Eleventh Southeastern Conference on Theoretical and Applied Mechanics, Huntsville, Alabama, 7 April 1982.

21. "Application of High-Speed Videography for Study of Complex, Three-Dimensional Water Flows", 15th International Congress on High-Speed Photography and Photonics, International Society for Optical Engineering, San Diego, Calif., 21 August 1982.

22. "The Effects of Sublayer-Scale Streamwise Surface Modifications on Turbulent Boundary Layers", AFOSR-ONR Workshop on Drag Reduction, National Academy of Science, Washington, D.C.

23. "Computer Augmented Hydrogen Bubble-wire Flow Visualization of a Turbulent Boundary Layer," 35th Annual Meeting, Division of Fluid Dynamics, Amer. Phys. Soc., Rutgers, N.Y., 23 November 1982.

24. "A Study of Loop Vortices Generated in a Hemisphere Wake," 35th Annual Meeting, Division of Fluid Dynamics, Amer. Phys. Soc., Rutgers, N.Y., 23 November 1982.

25. "Effects of Streamwise Surface Modifications on Turbulent Boundary Layers", 35th Meeting of Fluid Dynamics, Amer. Phys. Soc., Rutgers, N.Y., 24 November 1982.

26. "A Synthesis of the Near-Wall Structure of Turbulent Boundary Layers", Invited Seminar, VPI, Blackburg, VA, 10 December 1982.

27. "The Near-Wall Region of Turbulent Boundary Layers", Invited Seminar, Ohio State University, Columbus, Ohio, 18 February 1983.

28. "Observation, Modification, and Synthesis of the Near-Wall Region of Turbulent Boundary Layers", Invited Seminar, NASA-Ames Research Center, Moffett Field, CA, 29 June 1983.

29. "Computer Augmented Hydrogen Bubble-Wire Flow Visualization of Turbulent Boundary Layers", Third International Symposium on Flow Visualization, Ann Arbor, MI, 8 September 1983.

30. "A Synthesized Model of the Near-Wall Behavior in Turbulent Boundary Layers", A Keynote Lecture at the 8th Biennial Symposium on Turbulence, Rolla, MO, 28 September 1983.

31. "Generation of Near-Wall Turbulent Structure by Synthetic Low-Speed Streaks", 36th Mtg., Div. of Fluid Dyn., APS., Houston, TX, 22 November 1983.

32. "Three-Dimensional Recreation and Dynamic Motion of a Single Hydrogen Bubble-Line", 36th Mtg., Div. of Fluid Dyn., APS, Houston, TX, 22 November 1983.

D.E. ABBOTT

1. "Theoretical and Experimental Investigation of Turbulent Boundary-Layer Structure-An Integrated Research Program," Thermal-Science Colloquium, Rutgers University, October, 1978.

2. "Investigation of the Fundamental Structure of Turbulent Boundary Layers," Ingersoll-Rand Corp., Phillipsburg, N.J., December, 1978.

3. "Specialists Workshop on Coherent Structure in Turbulent Boundary Layers", panelist, East Lansing, Michigan, July, 1979.

4. "Review of the A.F.O.S.R.-Lehigh University Program on Turbulent Boundary Layers," Lehigh University Research Center's Review, September, 1979.

5. "Boundary Layers," Technical Session Chairman, 32nd Annual Meeting, Division of Fluid Dynamics, American Physical Society, Notre Dame, Indiana, November, 1979. (Also elected Fellow, American Physical Society.)

C. THESES

Completed Theses

1. Scharnhorst, R.K., "An Analysis and Prediction of Nominally Steady, Two-Dimensional, Constant Property Turbulent Boundary Layer", Ph.D. thesis, Purdue University, Aug. 1978.

2. Doligalski, T.L., "The Influence of Vortex Motion on Wall Boundary Layers", Ph.D. Thesis, Lehigh University, October 1980.

3. Metzler, S.P., "Processes in the Wall Region of a Turbulent Boundary Layer", MSME thesis, Lehigh University, December 1980.

4. Schwartz, S.P., "The Detection and Quantification of Axial Vortices in the Wall-Region of a Turbulent Boundary Layer", MSME thesis, Lehigh University, June 1981.

5. Lee, W.C., "Two Improved Methods for Parabolic Equations", MSME thesis, Lehigh University, June 1981.

6. Yuhas, L.J., "An Optimization Technique for the Development of a Two-Dimensional Turbulent Boundary Layer Model", MSME, Lehigh University, October, 1981.

7. Wei, T., "The Presence of Secondary Vortices in the Wake of Circular Cylinders", MSME Thesis, Lehigh University, June 1982.

8. Johansen, J.B., "The Effects of Cylindrical Surface Modifications on Turbulent Boundary Layers", MSME Thesis, Lehigh University, December 1982.

9. Cerra, A.W. "Experimental Observation of Vortex Ring Interaction with Fluid Adjacent to a Surface", MSME Thesis, Lehigh University, September 1983.

Theses in Progress (expected completion date in parentheses)

1. Acarlar, M.S., "Creation of Synthesized Turbulent Structure Using Surface Modifications", Ph.D. thesis (June 1984).

2. Bogucz, E.A., "Numerical Methods for Turbulent Boundary Layers", Ph.D. thesis (Aug. 1984).

3. S. Ersoy, "The Motion and Effects of Multiple Vortex Boundary Layers", Ph.D. thesis (Aug. 1984).

4. Bacher, E.V., "The Effects of Drag Reducing Surface Modification on Near Wall Turbulent Boundary Layer Structure", M.S. thesis (Sept. 1984).

5. Lu, L.J., "Examination of Near-Wall Turbulent Boundary Layer Behavior Using Computer Analyzed Flow Visualization", M.S. thesis (Sept. 1984).

6. Hon, G.T., "The Boundary Layers Induced by Loop Vortex Filaments", Ph.D. thesis (Dec. 1984).

VI. PERSONNEL

A. Co-Principal Investigators

D.E. Abbott, Professor of Mechanical Engineering
C.R. Smith, Professor of Mechanical Engineering
J.D.A. Walker, Professor of Mechanical Engineering

B. Student Research Assistants

		(Comp. date)
S. Ersoy	Ph.D. Candidate	(Aug. 1984)
M.S. Acarlar	Ph.D. Candidate	(June 1984)
E.A. Bogucz	Ph.D. Candidate	(Aug. 1984)
G.T. Hon	Ph.D. Candidate	(Dec. 1984)
E.V. Bacher	MSME Candidate	(Sept. 1984)
L.J. Lu	MSME Candidate	(Sept. 1984)

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